THE RISE OF MODERN PHYSICS

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THE RISE
OF MODERN PHYSICS

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A Popular Sketch

BY

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in Northwestern University

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PREFACE

The plan and method of this book are simple in the extreme. It is intended for readers who have had little previous knowledge of the subject but who would be glad of an informal introduction to this fascinating science. It originated in the following manner. In 1919, at the suggestion of Dr. Lynn H. Hough, then President of Northwestern University, my late colleague, Professor William A Locy and I agreed to join in giving a course of lectures, for juniors and seniors, on the History of Science. Professor Locy had been lecturing with marked success for some years on the history of biology along the lines laid down in his two volumes, *Biology and its Makers* and *The Growth of Biology*. I entered upon this program with enthusiasm for I had never regarded physics as an abstract subject, but rather as a concrete human achievement. The course was to be addressed to undergraduates of some maturity who had more or less interest in science; but it was not to presuppose any special training on their part either in biology or in physics. The following chapters are the outcome of this plan; but, of course, they do not cover the subject with the same completeness as the lectures.

The author has constantly had in view two purposes. The first is to reduce to a minimum the accounts of mistaken viewpoints and outworn theories; the second is to introduce more of what the biologists call "connective tissue" than has hitherto been customary in histories of

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physics. Of these tasks the first would appear to be comparatively easy since the story of physics is practically free from those *mensonges convenables* which, as some distinguished Frenchmen assure us, enter so largely into the composition of political history. The second task is more difficult, partly because the dovetailedness of phenomena does not often appear until long after the discovery of these phenomena and partly because the facts which lead to new experiments and discoveries are frequently buried in oblivion.

When so many new and important things are at hand waiting to be done it is not easy to answer the question as to just how much time the consideration of the past deserves. All of us are probably agreed that the past must be kept in the background; and yet we are almost unanimous in thinking that the past must not be forgotten. A thing which is not to be forgotten must be known. The following pages represent what might be called an irreducible minimum for one who wishes to acquire a just perspective by not forgetting the past in physical science.

Two distinctly different views of the history of physics are entertained by physicists of the present day. From one standpoint, the science of physics is always taking its old theories to the scrapheap and is constantly creating new and better theories. This view is emphasized by a distinguished contemporary physicist who thinks that "the childish mechanical conceptions of the nineteenth century are now grotesquely inadequate."

From the other standpoint, our guesses at truth are found to be outlined, or at least adumbrated, in older theories. The adherents of this view find that the atomic theory, the doctrine of evolution, the mechanistic and vitalistic views of life, the monistic and dualistic views of the world all antedate the beginning of the Christian era.

The following pages hold that both these views are extreme and that progress has always been made by an increasing, but continuous, adaptation to environment. In the case of physics, this does not mean the complete abandonment of older experiences and judgments, but a constant modification of these so as to include both old and new. With this "enlargement of conceit," to use Sir Philip Sidney's phrase, many things which once appeared to be much alike are found to be very different; and many phenomena which are superficially different prove to be essentially identical. The constantly growing tree of science, so far from sending its old wood to the fire, preserves it and builds upon it through the cambium layer of new facts and better fitting theories. There are exceptions; but, as a rule, *ex pede Herculem*, one finds the leading physicists of the past, like those of the present, men of clear vision, wide grasp, unbounded energy, and inspiring character. The more one puts oneself in their place the more one marvels at their achievements.

Three of my colleagues have placed me under especial obligations. These are Dr. Walter Libby, now of Toronto, who has generously read all the galley proof and from his wide learning has given me numerous constructive criticisms; Mr. Ernest Lauer to whom I am deeply indebted for much helpful advice; and Dr. Theodore W. Koch who has allowed me to draw freely upon his valuable time and his accurate knowledge of the art of illustration.

To Professor Sommerfeld and the Deutsches Museum at Munich, to Professor Arthur Haas of Vienna, to Dr. Bronislawa Dluska of Warsaw, and to the Chemists' Club of New York, I want to express grateful acknowledgment for portraits which appear in the following pages.

HENRY CREW.

Northwestern University
Evanston, Illinois
November 5, 1927

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CHAPTER I

"The past at least is secure."
—DANIEL WEBSTER, *Reply to Hayne.*

INTRODUCTION

Whoever would understand the history of physics finds himself embarrassed at the outset by the meaning of the word. Is physics a thing of yesterday beginning with Newton's *Principia*, 1687, and Galileo's *Two New Sciences*, 1638, or does it go back to Archimedes? Did the builders of the Pyramid Age, 3000–2500 B.C., have a fairly good working knowledge of physics or must we proceed still farther up the stream of time to the men who invented the drill, the thrust drill, and the potter's wheel? The question is a fascinating one; but it belongs rather at the end than at the beginning of this volume.

Whatever the answer, we are at least all agreed that the study of these ancient times gives us a certain emancipation from our own age and that present day physics—even the physics of the electron and the quantum—never gets very far away from mechanics.

The early growth of physical science showed itself mainly through the solution of a large number of isolated household, industrial and commercial problems. How should one count time so as to know when his interest or his principal is due, how should he measure the area of the land which he is about to buy or how should he weigh the silver received for an ox which he is about to sell? The answer to these three questions introduces us at once to the three fundamental measurements of the modern physical laboratory, namely, those of *length*, *mass*, and *time*. It is perhaps not unfair therefore to say that the history of physics begins with the invention of any machines, the descriptions of any motions, the enunciation of any theories or the discovery of any principles which ameliorate life and clarify thought; which give us simplicity of view and free us from superstition. These things take us very far back, and raise the question as to what were the earliest machines.

Here again the meaning of the word bothers us; but if we rule out the inclined plane and the lever on the ground that they are so simple that they require very little ingenuity and, therefore, may be classed as tools rather than machines, the evidence which archaeologists have, up to the present, been able to obtain would seem to indicate that the earliest machines are the drill, the thrust drill and the potter's wheel, each of which antedates the Pyramid Age, 3000 B.C., in Egypt. The wheel as a burden-bearing device—that is the cart wheel—makes its appearance in Egypt later. It is clearly in use on chariots sculptured on the walls of the Great Hall of Karnak.

The stone blocks employed in the pyramids and other tombs of Egypt indicate a thorough mastery of the simple cutting tools, the discovery of hard metal, and the ability to use the roller, as well as sledge and boat for transportation. The want of more efficient labor saving devices was probably less felt on account of the abundance of slave-labor.

A somewhat similar uncertainty clouds our vision as we look into the more distant past. How we should delight to honor the man who first invented fire if only we knew his name and place! Equal mystery surrounds the man who made the first clay vessels, the man who first tamed the horse, the oarsman who first set up a mast and sail, the man who first observed that nearby sounds reach the ear in less time than those produced at a distance, and other pioneers in man's prehistoric career, which is variously estimated at from fifty to five hundred thousand years.

Somewhere between 5000 and 4000 B.C. begins a series of events of which we have at first a fragmentary, and then later a more or less complete, record. The history of civilization extends back therefore among the people most highly developed—that is, the races which occupied the lower valley of the Nile and country bordering the Tigris and Euphrates—over some six or seven thousand years.

THE MEASUREMENT OF MASS

The earliest balances known are probably those pictured in Egyptian sculptures, which represent the dead man in the presence of the great god Osiris, watching his soul on one pan of the balance being weighed against right and truth in the other pan. The jar on the left pan symbolizes the man's mind and heart; the feather on the right stands for truth and justice.

THE MEASUREMENT OF TIME

The three natural units which nature has supplied for the measure of time, the day, the month, and the year, are so patent that they have been used always, everywhere, and by everyone. Nevertheless they suffer from one serious defect; they are not commensurable; neither the month nor year contains a whole number of days; nor does the year contain a whole number of lunar months. Thus arose, at the very dawn of civilization, the difficult problem of the calendar—the problem of adjusting the relative lengths of the day and the year so that our count of the days shall keep step with the passages of the sun and our count of the years with the passages of the seasons. Not only so, the problem is further complicated by the fact that we have three different kinds of days, mean solar, apparent solar, and sidereal; and more than three kinds of years. The essential feature of all measurement is comparison; in this case the comparison of time intervals; but a time-interval is a fleeting thing and cannot be brought back, as a yard-stick, whenever needed. Hence the necessity of machines which will mark off equal time intervals. The demand for these machines renders the measurement of time a vastly more difficult process than the measurement of mass or length.

It is to the Egyptians that we owe the beginnings of our present calendar; for, instead of adopting a year of twelve periods of the moon, as used by the Sumerians, they introduced a year of twelve 30-day months, which gave them 360 days and left five holidays at the end of the year. We shall see later how European nations have modified this year. Machines for measuring small intervals of time—later called *clepsydrae*, water thieves—have been traced back to the reign of Amenhotep III (1415–1380 B.C.). These water clocks assumed a great variety of forms but they are all based upon the general principle that the amount of water escaping from a small aperture in a tank varies approximately as the time during which the flow takes place. Those tanks which were provided with some means for maintaining a constant level of water gave of course more accurate time intervals. Relics of this instrument are to be found in such Latin phrases as *aquam dare*, meaning to extend one's time and *aquam perdere*, to waste time. Sedgwick and Tyler, in their *Short History of Science*, page 40, quote an interesting remark from Demosthenes when interruped, "You there! Stop the water!"

MEASUREMENTS OF ANGLE

In all angular measurements the fundamental idea is the division of a circle into a convenient number of parts. The Chaldeans (606–539 B.C.) divided the equator into 360 degrees and also laid out the "Twelve Signs of the Zodiac." The graduation of an ordinary spectrometer circle is derived, therefore, from the valley of the Euphrates. To them we owe also the division of day and night into twelve hours each. Just how the Chaldeans happened to strike upon the sexagesimal system is not certainly known. Among the guesses which have been made are these:

(i) Because, in the most primitive times, the year was divided into 360 days, a year which of course soon got out of step with the seasons, but nevertheless made the sun's motion among the stars one degree a day.

(ii) Others have imagined that the system took its start from the fact that the inscribed hexagon naturally divides the circle into six equal parts.

(iii) Still others think it might have been suggested by the fact that the number 60 is divisible by all the small numbers up to and including 6.

BRIEF RÉSUMÉ OF PRE-GREEK CONTRIBUTIONS

From this brief sketch of what physical science owes to the two great civilizations which precede that of southern Europe, it will be seen that these contributions were mainly of an utilitarian character, consisting largely of mechanical arts and commercial devices. There is nowhere to be found any formulation of the behavior of nature, nothing in the way of physical law, no general view of any field. The Egyptians were clearly familiar with the "3·4·5· rule;" but there is no evidence that they were able to derive it from more general principles.[1]

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[1] Karpinski, L. C. *Al Khowarizmi*, p. 2.

CHAPTER II

GREEK AND ROMAN SCIENCE

> "The history of the intellectual world is the history of the worship of one idol after another."
>
> —A. DE MORGAN, *Budget of Paradoxes.*

The first people who were able to take the dry facts collected by the Egyptians and Babylonians and weave them into a science were the Greeks. Here at the very outset we meet one of the great mysteries of history. How did it ever happen that the Aryan people, who early settled the Greek peninsula and that part of the west coast of Asia Minor, known as Ionia, were able to cut loose from tradition and superstition and to think about physical phenomena in a thoroughly rational and commonsense manner? How did such a highly intellectual world come into sudden being somewhere between 800 and 600 B.C.? Or was there a gradual growth of which the world has lost all record? How did these people, who spoke the language of Homer, suddenly acquire a keen curiosity as to the manner in which the universe is built and operated? Whence this interest in general principles? Whence these numerous followers of Ulysses making excursions into the various realms of the intellectual world?

The answers which these questions have received can hardly be called satisfactory. Some historians have attempted to find an explanation in the genial climate, the fertile soil, and abundant leisure to talk things over in the market place and about the town pump. Archaeologists have traced back through several centuries the slow displacement of the pre-Greek inhabitants of the peninsula by the Greeks themselves; but the problem remains.

So far as the history of physics is concerned, these first great thinkers fall rather naturally into three groups; the Ionians, the Pythagoreans, and the Alexandrians.

I. THE IONIAN SCHOOL

The Ionians must always be reckoned the first great thinkers of Europe; and first among them comes Thales, whom Aristotle describes as the man who initiated the investigation of nature. His birthplace was Miletus, a few miles south of the present city of Smyrna on the west coast of Asia Minor and, in those days, the greatest Greek city in the world. Here Thales was born about 640 B.C. Very little is known about the man; none of his writings are extant; indeed it is not even known that he left any writings. What information we have is mainly from the writings of Diogenes Laërtius, who lived eight centuries after Thales and who says that Thales was "the first to converse about natural philosophy, as some say. But Aristotle and Hippias say that he attributed souls to lifeless things, forming his conjecture from the nature of the magnet and of amber. He asserted water to be the principle (*'αρχη'*) of all things and that the world had life and was full of demons."[1] [*πάντα ὕδωρ ἔστιν.*]

The importance of Thales' suggestion lies mainly in the fact that it is a serious attempt to reduce the evident complexity of the physical world by the introduction of a unifying substance—water. For the first step in the creation of science is a profound faith in a definite order in nature. Other members of the same school suggested other substances. Anaximander (*c.* 611–547 B.C.) proposed to reduce everything to an infinite something different from water. Axaximenes, near the end of the sixth century B.C., considered air as the one substance capable of satisfying the quality of infinity put forth by Anaximander.

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[1] C. D. Younge's translation of Laërtius Diogenes in Bohn's Classical Library.

Heraclitus (*c.* 540–475 B.C.) who flourished at Ephesus, a city about midway between Miletus and Smyrna, belongs to this same school; and although practically nothing is known of his life, many of his sayings have come down to us and they clearly indicate that he made a courageous attempt to master experience by describing the universe as an eternal series of changes, an idea which is generous enough to include everything from the kinetic theory of gases up to organic evolution. This *constant change* of Heraclitus is aptly typified by the flickering flames of a fire. "You cannot step twice into the same river," he says. "All things are, and nothing remains." "The senses are bad witnesses" (κακὸι μάρτυρες).

Parmenides who seems to have been born about 539 B.C., and who was, therefore, a contemporary of Heraclitus, was also a searcher after the constant element in nature. He explains his ideas in a poem of which some 160 lines have been preserved. Here he sets forth the curious view that only that which is, is continuous, uncreated, whole and indivisible; and that, therefore, all change, variety, and mutation belong to the non-existent. The entire doctrine of Parmenides is summed up in his phrase "the Ent is, the Non-ent is not."

Heraclitus and Parmenides represent therefore two extremes; one explains the world in terms of perpetual change and preaches the gospel of flux; the other reduces the universe to one constant thing, the existent, and treats all creation and alteration as pure fictions of the mind.

In the practice of contemporary physics, we find a clear recognition and union of both these views. The modern investigator is always seeking to discover what it is that remains constant in the midst of ever varying phenomena. Boyle's law is merely a statement of what is observed to remain constant while the volume of a gas varies with the pressure to which the gas is subjected.

It is a far cry from Heraclitus and Parmenides to G. R. Kirchhoff (1824–1887); and yet one is bound to admit that this fundamental and uniform fact of nature—constancy and change—is more or less reflected in the celebrated definition of mechanics given by this eminent German physicist, namely, "the simplest and most complete description of the motions one meets in nature."

In the same way, a later pupil in the Ionian School, Protagoras (*c.* 481–411 B.C.), the sophist, insists that "man is the measure of all things, of what is that it is, and of what is not that it is not." One is tempted to see in this remark an anticipation of modern relativity; but it must be remembered that in all of Einstein's doctrine man is left completely out except as he is introduced in a purely incidental and objective way as a measuring machine.

The group of Ionian "physicists," at which we have just taken a glance, set about to discover the substance which underlies all things; they were followed by a second group whose aim was rather to discover the cause of this observed multiplicity and change. That the world is not so simple as it had been pictured up to date is first made clear by Empedocles (*c.* 490–430 B.C.) who, though not an Ionian by birth, was one with them in his mode of thought. He was, in fact, an eminent statesman, physicist, and physician, born at Akragas—modern Girgenti—on the southern coast of Sicily, then a Greek colony. A man of great sympathy with the people, the Italians consider him the greatest democrat of antiquity.

The cosmos he explained in terms of four elements—earth, air, fire, and water. To these elements he adds two divine powers—the principles of attraction and repulsion which he supposes to pervade the entire world, furnishing two opposing forces, just as love and hatred do for human beings. Few ideas in physical science have played a more conspicuous part, and perhaps none for a longer time, than these four—really six—elements of Empedocles. However, his analysis was as Whewell says merely "a decomposition of the body into adjectives and not into substances."[2]

Fanciful as all this may appear to us, it is well to remember that *cohesion*, *adhesion*, *chemical affinity*, and *gravitation* are to us little more than names to designate processes we do not understand. What matters it whether we call it "cohesion" or "love"? What advantage has *electric repulsion* over *hate?* Or consider the following words which Boyle[3] puts into the mouth of Themistius—the character who represents the peripatetics:

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[2] *History of the Inductive Sciences*, II, p. 261.

> "For if you would but consider a piece of green wood burning in the chimney, you will readily discern, in the disbanded parts of it, the four elements, of which we teach it and other mixed bodies to be composed. The *fire* discovers itself in the flame; the smoke, by ascending to the top of the chimney and there readily vanishing into *air*, like a river losing itself in the sea, sufficiently manifests to what element it belongs and gladly returns. The *water* in its own form boiling and hissing at the ends of the burning wood betrays itself to more than one of our senses; and the ashes by their weight, their firiness, and their dryness, put it past doubt that they belong to the element of *earth*."

These views proved to have no permanent value; not because they lacked naturalness, but because they were never submitted to the test of thorough experiment. At that period the testimony of experience carried small weight in the high court of reason. The senses were bad witnesses. To resort to experiment was to stoop. What one sees and hears and smells and feels is only a part; reason must be trusted as the one reliable guide.

Note that Greek science and Greek poetry grow up together. If one prefers to be more particular about dates, he can say that poetry had its start in Homer and Hesiod, but flourished and matured at the same time with the best of Greek science. Empedocles writes in hexameter. Five hundred lines of his are extant. The same is true, as we shall see later, in Roman science where Lucretius explains the atomic theory in verse.

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[3] *Sceptical Chymist*, p. 21, Everyman's Library.

The Ionian school reached its climax in a group of three men who suggested, created, and explained an atomic theory which, in spite of its many modifications, has been one of the corner stones in the science of physics from that day to the present. The first of these was Anaxagoras (born *c.* 500 B.C.) of Clazomenae, some twenty miles west of Smyrna, who had some influence in establishing a belief that all the masses of the universe might be divided into infinitesimal particles. Nevertheless we are bound to consider Leucippus (flourished fifth century B.C.) the creator of the atomic hypothesis. Although next to nothing is known about him three cities—Abdera, Elea, and Miletus—contended for his birth. Aristotle makes it clear that Leucippus championed the doctrine that the ultimate constituents of all things are empty space and atoms. Growth and decay consist merely in the rearrangement of atoms.

The third member of the trio was the great pupil of Leucippus, Democritus (born 465 B.C.), the last of the so-called physical philosophers and the culmination of the Ionian school. He was born at Abdera in Thrace, travelled widely over the then known world and spent no less than seven years of study in Egypt. The physicist's chief interest in Democritus lies in the fact that he was the first to establish a complete atomic theory, basing it upon a set of eternal, indivisible, invisible, and incompressible atoms, which derive their name, of course, from their assumed indivisibility. Besides these atoms which differ in *shape*, *position*, and *arrangement*, nothing in the universe exists except empty space. Liquids are composed of round atoms; the solid metal, of atoms with locks on them. Someone[4] has compared the differences between bodies to the differences between a comedy and a tragedy each of which contains the same letters. Life itself is maintained by inhaling and exhaling atoms; once a fresh supply of these atoms is cut off, death follows.

The system of Democritus, it will be seen, is more purely materialistic than that of either of his predecessors; and while it represents a more or less definite attempt to adapt itself to the observed facts, it must not be forgotten that the experimental evidence for this theory—the impersonal verification—to use Dr. C. S. Minot's phrase—was obtained only in the year 1808 when Dalton published his *New System;* and that the conservation of matter, also a part of Democritus' theory, was not established until the time of the French Revolution. The ideas of Democritus, so far as physics is concerned, developed slowly and began to bear fruit only in modern times, when they were taken up by Pierre Gassendi (1592–1655), though, in the meantime, they had served as a foundation for one of the four main schools of Greek philosophy—the Epicurean.

II. THE SCHOOL OF PYTHAGORAS

The founder of the second of the three Greek schools that have especially influenced the trend of thought in physics was also an Ionian. The authentic details of Pythagoras are meagre enough; but it appears to be fairly established that he was born on the island of Samos just off the coast of Asia Minor about the year 582 B.C., that he migrated to Crotona in southern Italy about the year

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[4] *Encyclopaedia Britannica,* 11th edition, "Democritus."

530 B.C., and that he there organized and stimulated a group of intellectuals which maintained its existence until the middle of the fourth century. The doctrines of this school were not narrow; they covered such diverse fields as ethics, music, astronomy, geometry and arithmetic. We have nothing from Pythagoras himself, and most of what is reported by later writers is hazy and fantastic. Their one important contribution to physics is the dominant idea that the relations of things are best expressed, where possible, in numbers, that the great uniformities of nature are properly described only when they are described quantitatively. The fruitfulness of this view, which elevated mathematics to a science and which lies at the very base of modern mathematical physics, is splendidly demonstrated by such Alexandrians as Euclid and Archimedes. My distinguished colleague, the late Dr. Charles J. Little, was fond of insisting that accuracy is the first step in morality; and in this respect he was a good Pythagorean. The classification of numbers introduced by Pythagoras gives a certain unity to the ancient quadrivium and is perhaps the basis of the quadrivium, namely,

$$\left.\begin{array}{l}\text{1. Absolute numbers} = \text{arithmetic}\\ \text{2. Applied numbers} = \text{music}\\ \text{3. Magnitude at rest} = \text{geometry}\\ \text{4. Magnitude in motion} = \text{astronomy}\end{array}\right\} = \text{Quadrivium.}$$

Zeno, born about the beginning of the fifth century B.C., is classified by philosophers as a member of the Eleatic school but so far as his legacy to physics is concerned he belongs with the Pythagoreans. For by a series of *paradoxes*, some eight of which survive, he taught all succeeding generations the futility of treating continuous quantities by means of discreet numbers and he pointed out certain difficulties inherent in the conception of infinity, which have kept mathematicians busy for two millenniums and have warned physicists not to use this quantity at all. The story of Achilles and the tortoise is familiar to every reader; this and several paradoxes of Zeno's have been interpreted in an interesting manner by Professor Florian Cajori.[5] Here will be found also the matured judgment of P. Tannery who has made it highly probable that Zeno's efforts were entirely directed against the conception of space as a sum of points, and time as a sum of instants.

Digression on Socrates, Plato and Aristotle

If we except the great creators of literature, the three outstanding intellects of the fifth and fourth centuries B.C. are doubtless those named at the head of this paragraph; and yet physics owes almost nothing to any one of them. The Athenians were interested mainly in humanism. Why then digress? Simply in order to get their attitude of mind toward this science.

All that we know of Socrates (471–399 B.C.)—intellectually the acutest man of his age—is contained in the writings of Xenophon (*c.* 430–355 B.C.), Plato (427–347 B.C.) and Aristophanes (*c.* 448–385 B.C.). All that Socrates and his distinguished pupil have to say on the subject of physics is contained in Plato's dialogue, the *Timaeus*. The name, Timaeus, is that of the principal interlocutor. One might imagine the views of these two men to be easily discovered by reading this dialogue; the fact is, however, quite the reverse. The meaning of Plato is thoroughly obscure even in the excellent translation by Jowett.

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[5] *Isis*, 3, January, 1920.

In estimating the views of the ancients, we must ever bear in mind that they were sadly deficient—one dares not call the Greeks ignorant—in knowledge of the ordinary every-day facts concerning materials and processes. The entire range of science in those days included only a few fragments of geometry, medicine and astronomy. Yet in spite of this twilight knowledge, as Jowett calls it, they were attempting to see the universe and see it whole. Jowett says,

> "Nature in the aspect which she presented to a Greek philosopher of the fourth century before Christ, is not easily reproduced to modern eyes. The associations of mythology and poetry have to be added, and the unconscious influence of science has to be subtracted, before we can behold the heavens or the earth as they appeared to the Greek. The philosopher himself was a child and also a man, a child in the range of his attainments, but also a great intelligence having an insight into nature, and often anticipations of the truth."

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> "The great source of error and also the beginning of truth to them was reasoning from analogy; they could see resemblances, but not differences; and they were incapable of distinguishing illustration from argument. Analogy *in modern times* only points the way and is immediately verified *by experiment*."[6]

It has become quite the fashion in these days for the man of science to make light of metaphysics; and yet the evidence all seems to point to the fact that metaphysics necessarily precedes physics in the development of human thought. Before a man can explain the world, he must learn that the universe is something larger than his own person, larger than the room in which he is living, larger than his own village or country side, larger even than the whole earth. Before one can explain stones, and brooks, and winds, he must learn to conceive matter. To discover the real similarity between birds, and horses and fish; or to realize the many striking resemblances between plants and animals, one must have as an antecedent a general conception of life and animate matter. But these metaphysical conceptions come slowly; the Greeks had just acquired them in the time of Socrates and Plato; the first group of physicists, Thales *et al*, had just produced such concepts; and were just beginning to *observe* the world; they had not yet learned to experiment.

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[6] Dialogues of Plato, II, pp. 486–488.

When we bear this in mind, it is all the more remarkable that they had gotten so far as to discover such facts as the similarity of the earth to other heavenly bodies, the rotation of the earth, and the dependence of musical pitch in a stretched string upon its tension and its length.

Then too it must never be forgotten that the range of experimental facts known to the ancients was very limited compared even with that which is now familiar to every high-school lad. It is, therefore, only natural that the Greeks of antiquity should rely mainly upon speculation. This habit led them directly to mathematics and metaphysics in which fields they achieved their most important results. To the Greeks in general and to Plato in particular, mathematics owes the high place which, ever since their time, it has held in education.

Besides this fact we have to remember that they had no art of printing by which to hand on knowledge. Hence they relied largely on their individual pupils; and this in turn led to the establishment of individual schools of thought—notably the Stoics Epicureans, Platonists and Peripatetics.

Of all the Greek schools, before the beginning of the Christian era, the Peripatetics showed perhaps the most sympathy with what we now call the method and the views of modern physical science; and this school persisted in a certain sense much longer than any of the others, extending entirely through the middle ages. But soon after the beginning of the Christian era it lost much of its virility, and practically adopted, as its main tenet, blind adherence to the views of its founder.

Aristotle (384–322 B.C.), who was born in the town of Stagira up in Macedonia, shares with Empedocles and Euclid the distinction of having influenced thought and of having his views taught in the schools for more than twenty centuries. At the age of seventeen, he came to Athens to study in the *Academy* under Plato. At the age of forty-two, he was summoned by Philip of Macedon as a tutor for his son Alexander, afterwards called Alexander the Great; and, as will be seen later, the influence of this friendship between Alexander and Aristotle upon both the Christian and Mohammedan worlds was so profound that there is small liklihood of our over-estimating it.

His contributions to science were, however, mostly in fields other than physics. His *physics*, so-called, denotes not the science which we know by that name, but rather the content of the Greek word φύσις, *Nature*; and includes not only mechanics, but also meteorology, astronomy, physiology, and anatomy.

To obtain any conception of his mechanical ideas one must follow through one or more of the thirty-six solutions included in his collection of *Mechanical Problems*. It has been shown that this treatise is more than likely spurious, but at any rate, these problems illustrate the *kind* of mechanics in vogue at the time of Aristotle.[7]

The following appraisal of Aristotle by Dr. Charles Singer is one of unusual accuracy.

> "Yet I will venture to sum up in a sentence what I believe to be the conclusions of the overwhelming majority of modern Aristotelian scholars and of scientific men who have investigated the works of the master: *Aristotle's physical science is almost worthless from the modern point of view; it has scarcely any serious basis of observation and none of experiment; his biological works, on the other hand, show him to have been an admirable and careful observer of animal life.* He was an excellent naturalist but a very poor physicist. I will further endeavor to epitomise the verdict of most scientific students of the Middle Ages on his position in medieval science. *It was chiefly Aristotle's physical works that earned for him his scientific reputation in the middle ages; his biological works exerted little influence until the sixteenth century.* Those who assent to these propositions will not agree that 'we have to appreciate better *medieval* regard for him.' "[8]

III. THE SCHOOL AT ALEXANDRIA

The story of Alexander the Great (356–323 B.C.) and of the important Greek city which he established at the mouth of the Nile in 332 B.C. is too well known to need recital here. Upon the death of Alexander, his kingdom was divided into several parts, and Egypt fell to one of his generals, Ptolemy Soter. It was this Ptolemy and his son, Ptolemy Philadelphus, often called Ptolemy II, who are mainly responsible for getting together the teachers and the library which constituted this remarkable seat of learning, the greatest university of its time and one which maintained its supremacy during four centuries. In the history of human thought the *Museum* of Alexandria will always have a place with the *Grove* and the *Porch* of Athens. The institution was essentially Greek, and though science had emigrated from Athens to Alexandria, the Greeks were still in the saddle and remained there until the place passed under Roman jurisdiction in 80 B.C., shortly before the flirtation of Ceasar and Cleopatra, 47 B.C.

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[7] E. S. Foster's translation of Aristotle's *Mechanics*, Oxford University Press, 1913.

[8] *Nature*, 105, p. 548, 1920.

The great ornament of the city was of course the group of scholars who there cultivated mathematical, physical and literary studies.

Euclid

Four of these names are outstanding for every student of physics. The first of these is Euclid, concerning whose life we know practically nothing except the fact that he flourished about the year 300 B.C. and that he taught mathematics in Alexandria during the reign of Ptolemy I. Euclid's *Elements*, in thirteen books, follows the logically rigorous method recommended by Plato and has been the acknowledged model of mathematicians for twenty centuries. The standard English edition has during recent years been that of Sir Thomas Heath (Cambridge, 1908).

The *Optics* attributed to Euclid by Proclus is possibly spurious, nevertheless the five following propositions from that work will probably give one a fair picture of the views which were current during Hellenistic times when light was thought to be something emitted by the eye, something sent out to examine into the nature of the body and bring back a report to the observer.

(i) Light travels in straight lines which lie at a certain distance from each other.

(ii) The figure enclosed by light rays is a cone, the apex of which lies in the eye.

(iii) Only those objects are visible which lie in the path of the rays.

(iv) The apparent size of an object depends upon the visual angle under which it is seen.

(v) A coin at the bottom of a cup may be lifted into sight by pouring in water.

It is easy to criticise any of these statements except possibly the last, the second, in fact, is just the contrary of what we now believe to be true, nevertheless one cannot fail to recognize here a courageous attempt to establish a one-to-one correspondence between the description and the facts. How thoroughly the Greeks mastered the facts as they discovered them, is illustrated by the story told by Cleomedes (*c.* 50 A.D.) concerning a lunar eclipse observed while the sun was still above the western horizon. The question at once arises as to how the sun, earth and moon could appear out of line if eclipses are really caused by the earth stepping in between the sun and the moon. Cleomedes refers the phenomenon to the fifth statement of Euclid mentioned above and cites the case of a rod being apparently bent when partially immersed in water and a ring lifted above the bottom of a cup when water is poured in. In the case of the eclipse it is the moon which is lifted by the refracting atmosphere.

There is some evidence that even in these early times, possibly as early as Aristophanes (424 B.C.), crystal, that is, quartz, spheres were used to kindle altar fires.[9]

Archimedes

It is a rather remarkable fact that of all the various subjects which from the earliest times have been treated under the head of physics—such as *mechanics*, *sound*, *capillarity*, *heat*, *light*, *electricity*, *magnetism*, only two, *light* and *mechanics*, were at all cultivated by the ancients. In Euclid, we have an illustration of what they did in optics, in considering Archimedes (287–212 B.C.) and his times we shall see what they did in mechanics. The dynamical views of the Greeks at this period represent them perhaps at their very worst. A tract wrongly attributed to Euclid, but probably belonging to his time, sets forth the fundamental principles of mechanics in the following definitions and propositions:

> "Bodies are equal, different, or greater in size according as they occupy equal, different, or greater spaces (1–3). Bodies are equal in *power* or *virtue* which move over equal distances in the same medium of air or water in equal times (4), while the *power* or *virtue* is greater if the motion takes less time, and less if it takes more (6). Bodies are *of the same kind* if, being equal in size, they are also equal in *power* when the medium is the same; they are different in kind when,

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[9] Baden-Powell, *Optics*, p. 66; *Encyclopaedia Britannica*, art. *Light*, p. 610.

> being equal in size, they are not equal in *power* or *virtue* (7, 8). Of bodies different in kind, that has more *power* which is more dense (*solidius*) (9). With these hypotheses, the author attempts to prove (Propositions 1, 3, 5) that, of bodies which traverse unequal spaces in equal times, that which traverses the greater space has the greater *power* and that, of bodies of the same kind, the *power* is proportional to the size, and conversely, if the *power* is proportional to the size, the bodies are of the same kind."[10]

Puerile as these theorems appear to the modern mind, they reflect very fairly the opinions of Aristotle which were accepted by all western Europe up to the time of Galileo.

Into this atmosphere was born Archimedes at Syracuse, down on the southeast coast of Sicily about 287 B.C. One has only to turn the pages of Archimedes' *Works*, especially in the splendid definitive edition of Sir Thomas Heath (Cambridge University Press, 1897) to discover that the problems which he attempts are always difficult and that his solutions are new and powerful in method. He says very little about himself, and not a great deal is known about him, nevertheless it is certain that he spent considerable time at Alexandria, that he had numerous friends there, among them Aristarchus and Eratosthenes, great astronomer and great geographer respectively. It was at Alexandria that his books were published, and it was there in all probability that many of his inventions were brought out, notably his water-screw. A host of stories concerning him have come down to us from many sources, principally incidents mentioned in the lives of other men by Plutarch, Livy and later writers. These accounts picture him as exceedingly absent minded, highly ingenious, devoted to pure science and contemptuous with regard to all applications. Among these uncertain traditions are to be classed the bathtub yarn, *εὕρηκα*, and the remark that he could lift the earth if only he had a place to stand, *δός μοι ποῦ στῶ καὶ τὴν γῆν κινήσω*; also his feat of firing the Roman ships by means of concave mirrors.

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[10] Heath, *History of Mathematics*, I, p. 445.

It will be generally conceded that his most noteworthy contributions to science are along mathematical lines; but when one considers that he laid the foundation of theoretical mechanics, that he discovered the most fundamental principle of hydrostatics, that he arrived at the principal theory of moments, and perfected a rigid process of integration, that known as the method of exhaustion, capable of many applications in mechanics, it will be clear that he must always rank high as a pioneer physicist.

All that Archimedes' theory of moments lacks to make it general and complete is the accurate definition of the arm, as the perpendicular distance from the axis to the direction of the force, an amendment which was first made by Father Benedetti (1530–1590). Everything that he does is clear and correct as far as it goes. His hydrostatic principle is nothing less than an application of the Second Law of Motion to a floating body, $\Sigma\ (F) = 0$; this answers completely the question as to how far a ship will settle down in the water when launched. Not satisfied with this, he goes farther and answers the question, in certain cases, as to what position the body will assume when it floats. His answer to this query is a very close approach to the modern answer, namely, the sum of all the torques, as well as the sum of all the forces, must be zero before the floating body comes into equilibrium. $\Sigma (L) = 0$.

No one can really appreciate the great flight of the human mind which is represented by Archimedes' anticipation of the integral calculus until he has followed through one of his quadratures—say that of the parabola.[11] Here will be found the simple argument by which Archimedes divides a parabolic segment into narrow infinitesimal strips and balances them, in thought, one by one against a set of infinitesimal strips from a known triangle so that the theory of moments is called into play to show that the area of the parabolic segment is one third that of the definitely known triangle. This is called a "mechanical proof." He next proceeds to give a second demonstration of this same theorem by cutting up the segment of a parabola into inscribed and circumscribed infinitesimal trapezia and showing that, in the limit, the sum of these trapezia (i.e., the area of the segment) will balance a known triangle provided the segment has an arm three times as long as the arm of the suspended triangle. This leads easily to the desired area of the segment of the parabola. Lastly he substitutes for an infinite sum of infinitely small quantities —as employed in the two preceding cases—an infinite sum of finite but rapidly diminishing quantities, namely, a set of triangles inscribed in the segment of the parabola, which finally "exhaust" the entire area of the segment. By this method of exhaustion he shows that the area of the seg-

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[11] Heath, *Works of Archimedes*, pp. 241–246, Cambridge University Press, 1897; or Heath, *Greek Mathematics*, vol. 2, pp. 29–30, pp. 85–91, Oxford, 1921.

ment of a parabola is neither greater nor less than four-thirds the area of a certain triangle, namely, the triangle which has the same base as the segment and an equal height.

As illustrating the tremendous advance in clear dynamical thinking which Archimedes had made beyond Aristotle, consider the following eight propositions which are taken from his two books on the subject of floating bodies:

Postulate 1

Let it be supposed that a fluid is of such a character that, its parts lying evenly and being continuous, that part which is thrust the less is driven along by that which is thrust the more; and that each of its parts is thrust by the fluid which is above it in a perpendicular direction if the fluid be sunk in anything and compressed by anything else.

Proposition 1

If a surface be cut by a plane always passing through a certain point, and if the section be always a circumference of a circle whose centre is the aforesaid point, the surface is that of a sphere.

Proposition 2

The surface of any fluid at rest is the surface of a sphere whose centre is the same as that of the earth.

Proposition 3

Of solids those which, size for size, are of equal weight with a fluid will, if let down into the fluid, be immersed so that they do not project above the surface but do not sink lower.

Proposition 4

A solid lighter than a fluid will, if immersed in it, not be completely submerged, but part of it will project above the surface.

Proposition 5

Any solid lighter than a fluid will, if placed in the fluid, be so far immersed that the weight of the solid will be equal to the weight of the fluid displaced.

Proposition 6

If a solid lighter than a fluid be forcibly immersed in it, the solid will be driven upwards by a force equal to the difference between its weight and the weight of the fluid displaced.

Proposition 7

A solid heavier than a fluid will, if placed in it, descend to the bottom of the fluid, and the solid will, when weighed in the fluid, be lighter than its true weight by the weight of the fluid displaced.

BOOK II. PROPOSITION 1

If a solid lighter than a fluid be at rest in it, the weight of the solid will be to that of the same volume of the fluid as the immersed portion of the solid is to the whole."[12]

The postulate, it will be observed, is a careful definition of a fluid; Proposition 1 is purely mathematical; Proposition 2 points out clearly that the surface of any liquid at rest is part of an equipotential surface and is not flat, but curved; Proposition 3 defines bodies of equal density; Proposition 4 states an experimental fact; Proposition 5 is what we would now call an application of Newton's Second Law of Motion to a floating body; Propositions 6 and 7 are special cases of Proposition 5. Sir Thomas Heath regards Proposition 7 as the one employed by Archimedes in determining the proportions of gold and silver in the crown submitted to him for his opinion. The method is as follows:

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[12] Heath, *Works of Archimedes*, pp. 253–263.

$$\left.\begin{aligned}\text{Let } W &= \text{the weight of the crown}\\ w_1 &= \text{the weight of gold in it}\\ w_2 &= \text{the weight of silver in it}\end{aligned}\right\}\text{ whence } W = w_1 + w_2$$

Then make the three following measurements:

(i) Take an equal weight W of pure gold and weigh it in a liquid. Let F_1 denote the weight of the liquid displaced; the weight of liquid displaced by a weight w_1 of gold is therefore $\frac{w_1}{W} F_1$.

(ii) Next take the same weight of pure silver W and weigh it in the same fluid; let F_2 denote the loss of weight, i.e., the weight of fluid displaced. Then the fluid displaced by a weight w_2 of silver will be $\frac{w_2}{W} F_2$.

(iii) Weigh the crown itself in the same fluid and denote the loss of weight by F.

Now equate the two partial displacements to the total displacement and one has

$$\frac{w_1}{W} F_1 + \frac{w_2}{W} F_2 = F$$

Whence, remembering that $W = w_1 + w_2$, it follows that

$$\frac{w_1}{w_2} = \frac{F_2 - F}{F - F_1}$$

Where $\frac{w_1}{w_2}$ is the proportion sought.

Hipparchus

Astronomy is an important branch of physical science and is so closely related to physics proper in its early as well as in its later development (astrophysics) that one cannot fairly separate the two. In these days everybody knows that the water-tight partitions separating the different physical sciences are pure fictions of the college catalog.

Hipparchus (*fl.* 146–126 B.C.) was not only the first modern astronomer but was also the first master of kinematics. He was born in Bithynia, at Nicaea, something like one hundred miles southeast of the present city of Constantinople. Most of our information concerning him comes from Ptolemy, the other major astronomer among the ancients; and from him we learn that the observational activity of Hipparchus lay between 160 and 125 B.C. No recent thinker has realized any more clearly than Hipparchus that nothing in science is so fundamental as the facts of the case.

First of all Hipparchus discovered the fact that the two methods employed by the ancients for determining the length of the year do not give the same value.

(i) The first of these methods is to measure the interval between two successive summer solstices or two winter solstices. This interval was readily determined by observing the times at which the length of the shadow of a gnomon was minimum or maximum; and this period was called the *tropical* year. The method of determining the equinoxes at the great Alexandrian Museum was to set up a large thin wheel, parallel to the plane of the equator, so that a star at the pole would shine perpendicularly upon it. Its inclination to the vertical was then the latitude of Alexandria, approximately 30 degrees. Equinox was indicated by the fact that the shadow of the upper edge just covered the lower edge.

(ii) The second method of measuring the year was to observe the positon of the sun among the stars at sunrise or sunset. Since it was well known to the ancients that the sun moves east among the stars at the rate of four minutes each day, the *sidereal* year was simply the interval between two successive appearances of the sun in the same part of any given constellation. It was by comparison of observations extending over many years that Hipparchus found the tropical year to be some twenty minutes shorter than the sidereal year.

Now the path of the sun among the stars was very well known to the ancients; the plane including this path is, of course, the plane of the sun's motion about the earth as we now say. It is known as the plane of the ecliptic. When one looks along the plane of the earth's *equator*, and sees the sun, he knows that he is looking along the line of intersection of these two planes, this view of the sun is possible only twice a year, once in the spring when, as we say, the sun crosses the equator going north, and again in the autumn when the sun goes south. The point in the sky which the sun occupies at the first of these instants is known as the *vernal equinox;* and this is taken as the zero from which the longitude of any star is measured around the great circle of the ecliptic. The angular distance of a star from the plane of the ecliptic is known as its latitude. Now Hipparchus was keen enough to infer from earlier observations that the stars were gradually changing their longitude as the years went by, while their latitude remained practically constant; and he pointed out, with rare acumen, that the vernal equinox was gradually slipping along the circle of the ecliptic at the rate of approximately 36 seconds of arc a year; the modern value is more nearly 50 seconds. This slipping is towards the west and therefore toward the sun, which is always moving east among the stars, and the motion is therefore called the precession of the equinoxes. The cause of this motion was not completely explained until the time of D'Alembert (1717–1783), but the kinematics of it was completely unravelled by the clear and powerful mind of Hipparchus who showed that the motion of the earth is essentially that of a boy's spinning top; the axis of the top corresponding to the axis of the earth; the horizontal plane of the floor corresponding to the plane of the ecliptic. Hipparchus' acceptance of the then common belief that the earth is the center of the universe does not in any way detract from the value of his observations.

The invention of trigonometry. It is to this eminent astronomer that we owe the invention of one of the most frequently used tools of physics—the science of trigonometry—a method for describing mathematically the relations between the sides and angles of a triangle. His activity showed itself here in the preparation of a "table of chords"; but when one recalls that the chord of any arc is twice the sine of half the angle subtended by that chord, it is at once clear that what Hipparchus really computed was a table of sines. Unfortunately this table has been lost and all we know about it is that it once existed. Few men realize what a powerful aid to clear thinking is furnished by such simple mechanical devices, so to speak, as trigonometry, the forms of algebra, the law of moments.

In the same class of intellectual tools belongs the idea of latitude and longitude for locating positions on the earth's surface—an idea which we again inherit from Hipparchus.

To measure the difference in longitude between two places he proposed the very valid idea of two observers—one at each place—making simultaneous observations on an eclipse of the moon. The difference in times of the eclipse when expressed in hours and multiplied by fifteen would give the difference of longitude in degrees. One here neglects the slight correction for parallax. Previous to this time, towns were located as being so many stadia or so many days' travel in a certain direction from some known starting point.

The prime meridian chosen by Hipparchus was naturally that which ran through his own observatory, located, it is generally supposed, on the island of Rhodes near the eastern end of the Mediterranean. For several centuries before Hipparchus, the Tin Islands—the so-called Cassiterides—had been referred to as the western limit of civilization. The identification of these islands is uncertain; probably they are to be identified with Cornwall.

Later this prime meridian was shifted to what was then considered the westernmost land on the earth, namely, the island of Hierro, sometimes called Ferro, in the Canary group 20 degrees west of Paris, or 60 miles west of the African coast. Still later each capital in Europe was taken as fixing the prime meridian for its own particular country. Recently, however, the whole civilized world has adopted the meridian through the observatory at Greenwich as the zero of longitude; a fact not without significance as regards international goodwill. The time used in Illinois, for example is Greenwich time—the time of the 90th degree west of Greenwich; we call it "Central Standard Time."

Another matter that was greatly cleared up about this same time was the length of the tropical year which for a long while had been regarded as just a quarter of a day longer than 365 days. Hipparchus discovered that the year was 5 minutes less than this, namely, $365^d5^h55^m$—a value which remained the standard for a full thousand years, that is until the time of Albatenius (850–929 A.D.) The modern value is $365^d5^h48^m46^s$. To obtain this correction Hipparchus used the observations of Aristarchus on the times of equinoxes and solstices some hundred and fifty years earlier. The detection of such a minute angular correction as this and the measurement of the minute precession of the equinoxes by the crude means at the disposal of Hipparchus must always be reckoned as among the really outstanding triumphs of the human mind.

From the death of Hipparchus, 126 B.C., to the birth of Ptolemy, 127 A.D., intervenes a couple of very barren centuries so far as physical science goes. Hero of Alexandria, who flourished in the second century of our era, exhibited great fertility in inventing all sorts of curious scientific toys—*tours de force* they must have been in his day—but it is doubtful whether his work includes any new contribution to knowledge unless he be credited with the invention of the siphon and the force pump. The chief works of Hero are his *Pneumatics* and his *Catoptrics*. The former of these describes some seventy-eight different devices which, Professor Lynn Thorndike thinks, were intended, not so much to divert and amuse, as to deceive and surprise the observer. An excellent and highly entertaining account of these clever tricks is given by Professor Thorndike.[13]

By this time Egypt had become a mere province of the Roman Empire and a serious decline of interest in science had already set in. About this time also the younger Seneca (3 B.C.–65 A.D.) wrote a book (*Naturales Questiones*) dealing with physical and biological problems; but it contains no essential contribution to physics. With the advent of Ptolemy, a contemporary of Marcus Aurelius, the school at Alexandria took on a new lease of life; for he was followed by Diophantus, Pappus, Proclus, Theon and Boethius, each of whom rendered a distinct service to science, albeit mostly outside the field of physics proper.

Claudius Ptolemy (*c* 127–151 A.D.)

No sketch of the history of physics would be fair that omitted mention of the second of the two major astronomers who lived and worked at Alexandria, Claudius Ptolemy, the man who set forth a system of the universe that was taught and believed in western Europe for full fifteen centuries. Ptolemy was completing his observations at Alexandria about the time that Galen (born 129 A.D.) came there to study medicine.

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[13] Lynn Thorndike, *History of Magic and Experimental Science*, I, pp. 188–193.

At the beginning of the Christian era it mattered not whether one considered the earth a sphere or a flat plane bounded by the river of the ocean as Homer has it; in either case it was practically limited on the west by the Fortunate Islands that is, the Canary and Cape Verde groups, on the north by the Ultima Thule (Shetland Islands), on the east by China, on the south by Ethiopia (present Abyssinia) and a *terra incognita* supposed to extend east from Africa to meet the eastern shore of China and thus make an inland sea of what we now call the Indian Ocean.

To map all the various regions of this surface, then known only through the itineraries and tales of travellers, and to locate the principal cities with exactness was a fascinating problem. This is exactly the problem which Ptolemy solved following the method of Hipparchus. A highly instructive copy of his map is given in the *Encyclopædia Britannica* Art. *Map*. His errors and distortions, arising always from defective data, are not the least interesting feature. The only wonder is that without compass, without any telescope, without telegraph, without any means of travel that was either rapid, easy, or safe he succeeded in drawing as accurate a picture as he did.

Trigonometry received a marked extension beyond the point where Hipparchus left it. Ptolemy *assumes* the fundamental law of plane trigonometry which in his terminology would run as follows: "In every triangle the sides bear to one another the same ratio as do the chords of twice the arcs which subtend the opposite angles," or as we may now say, the sides are proportional to the sines of the opposite angles. In addition to this, he proves the well known theorem for the sine of the sum of two angles—sometimes called Ptolemy's Theorem.

$$\sin (A + B) = \sin A \cos B + \cos A \sin B.$$

Trigonometry was still a very practical branch of learning; it had not yet become what it is today, an abstract science of circular functions. The circumference of the circle Ptolemy divided into 360 equal parts corresponding to our degrees, and he likewise applied the sexagesimal system to the *radius* of the circle dividing it into sixty equal parts; each of these was in turn subdivided into what were called, in Latin, first minute parts (*partes minutae primae*) and these were again subdivided into second minute parts (*partes minutae secundae*). Here we have the origin of our every day terms, "minute" and "second," the first of these was originally the first *small* interval of time, the other the *second* small interval, the one we have abbreviated to *minute*, the other to *second*. The phrase "second minute" instead of simply "second" was in use up to the time of Newton, 1687. "The sexagesimal fraction held its own as the fraction *par excellence* for scientific computation until the sixteenth century, when it was displaced by the decimal fraction in all uses except the measurement of angles."[14]

Ptolemy's monumental work is of course his treatise on astronomy in thirteen books. Here will be found his trigonometry, his geography, and his planetary theory. The title which the author gave to this work was The Mathematical Collection, ʽΗ μαθηματικὴ σύνταξις. Later writers, however, called it *The Great Compendium of Astronomy*, to distinguish it from another treatment which was then very popular at the school in Alexandria, *The Little Astronomy*, ‛ο μικρὸς ’αστρονόμος. The Arabs, several centuries later, were not satisfied to think of it as merely *The Great Astronomical Collection*, so they substituted "μεγίστη" for "μεγάλη" and named it *The Greatest Collection*, and using the Arabic article *Al* wrote it *Almagest*, the name by which this remarkable book has ever since been known. The text of the work has been splendidly and completely preserved, apparently through the fact that it was early appreciated and widely copied and was later taken up enthusiastically by the Arabs. It represents the highest order of work accomplished by the Alexandrian School. Its earliest commentator was Theon of Alexandria, father of the brilliant Hypatia. This must have been about 370 A.D. Since then it has been edited and reedited times without number, the first printed edition appearing at Venice in 1496. The latest revision is perhaps that found in Publication No. 86 of the Carnegie Institution, Washington, 1915.

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[14] H. B. Fine, *Number System of Algebra*, p. 93, 1890.

IV. RÉSUMÉ OF THE STATE OF THE SCIENCE OF PHYSICS AT THE END OF THE ALEXANDRIAN PERIOD

(i) As regards mechanics, which may still be thought of as the fundamental chapter in physics, it is evident that the chief advance was made by Archimedes and that his definite achievements were limited to statics. He owed nothing to his predecessors, for they scorned experiment and could therefore make little headway in any experimental science such as mechanics. The contempt of the earlier Greeks for what we now call the experimental method arose merely from their unlimited faith in pure reason. Any method of solving problems except by purely intellectual power was, in their estimation, unworthy and undignified. One who appealed to experiment rather than to his own logic, was regarded with the same disdain which a real sportsman feels for a man who dynamites a stream for black bass. Among the aphorisms which the Greek physician, Hippocrates (born 460 B.C.) has left us is the well known one which insists that "experiment is difficult and judgment uncertain." The reference here is to experiments upon the physician's own patients, but this same "difficulty" is reflected in the *Mechanics* of Aristotle where one finds no appeal to experiment, and also, as might be expected, no real advance in mechanics. Even Archimedes had so little respect for any method except that of pure mathematics that he has left us no account of those brilliant engineering operations said to have been carried out by him while the Romans were besieging his native city.

Only two methods of investigation were known to the ancients, one was the mathematical, the other was the philosophical. Accordingly when Archimedes comes to demonstrate the law of the lever he makes seven postulates and proceeds in the manner of Euclid, apparently unmindful of the fact that these various postulates are all purely experimental facts, most of which had been verified times without number. Nowhere in his demonstration does he reach any result whose validity exceeds that of the many measurements already made upon various levers.

Weight. The only mechanical quantities which the ancients appear to have measured with any considerable accuracy are *length*, *volume* and *weight* for each of which they employed a great variety of units and standards. Of these the one which is of chief interest to the student of physics is probably *weight*; for weight is the earliest type of force to be measured and is the one force in terms of which, until modern times, all other forces were measured. When a Roman wanted to know what force he was exerting on the beam of an oil press he measured it in terms of weight. The force required to set a catapult was measured, if at all, in pounds weight. The one instrument by which these comparisons were practically always made was the steelyard, essentially a beam balance still seen all over southern Europe. The Roman pound, *libra*, at the time of Augustus (63 B.C.–14 A.D.) was not far from 327 of our grams. The symbol *lbs.* by which we still indicate pounds avoirdupois is, of course, merely a contraction for *librae*.

The Roman architect, Vitruvius, and the Roman engineer, Frontinus (40–103 A.D.) describe, with considerable detail, various hoisting machines, pumps, water clocks and aqueducts; but it is not clear that either of these men made any contribution to the science of mechanics. Frontinus not only describes the construction of the aqueducts at Rome but he tells how to measure the amount of water delivered through the pipes branching from the mains, and he evidently understood in a general way the effect of what we now call "head" or pressure. Nowhere, however, does he deal with anything but steady motion and nowhere does the speed of the water explicitly appear. The foundation of hydrostatics, as well as that of the statics of solid bodies, had been laid long before by Archimedes.

The mechanics of the ancients may be briefly described as an art. They had no body of general principles—no theory—upon which they could rely. The remarkable roof of the Pantheon in Rome, built in the reign of Hadrian (117–138 A.D.) was designed upon precedents and models. Even models were used with the knowledge that they could not be relied upon when any serious change of dimensions was involved. Thus Vitruvius in his treatise on *Architecture*[15] says:

> "For not all things are practicable on identical principles, but there are somethings which, when enlarged in imitation of small models, are effective; others cannot have models, but are constructed independently of them, while there are some which appear feasible, but when they have begun to increase in size are impracticable, as we can observe in the following instance. A half-inch, inch, or inch-and-a-half hole is bored with an augur, but if we should wish in the same manner to bore a hole a quarter of a foot in breadth, it is impracticable, while one of half-a-foot or more seems not even conceivable."

The difficulty to which Vitruvius here alludes has been quite removed by the modern theory of structure and the law of similitude.

(ii) As regards acoustics, it appears to be well established that the Pythagoreans—and possibly their predecessors—were familiar with the fact that air is the medium through which sound is transmitted to the ear. Aristotle notes concerning this medium that the same sound can be heard at a greater distance by night than by day.

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[15] Morgan's translation, Book x, chapter 16.

The echo, of course, was known; and was personified by a mountain nymph who could speak only when she was spoken to and could then repeat only the last word of the speaker. The harmony of the major chord was recognized by Pythagoras who also knew that the octave was produced by shortening a stretched string to half its length; but as yet there was not the slightest conception of the nature of the connection between the physical make-up of a musical instrument and the tones which it emits.

The musical scale of the Greeks is a somewhat recondite subject and one which lies quite outside our present purpose. Those interested may find special articles on this subject.[16] The marked distinction between the word *music*, *μουσικη′*(sc. *τέχνη*), as it appears in Greek history and the same word in English is not to be forgotten. In the former case, it includes all those subjects which were presided over by the nine Muses, and is used in sharp contrast with gymnastics and grammar. *Music* was that branch of education which had to do with the cultivation of the mind; gymnastics had to do with the training of the body. Music to the Greeks, therefore, included science and literature as well as reading and writing, while that branch of sound which deals with the problem of pleasing the ear is denoted by *harmony*, again with a meaning somewhat different from ours. It is now clear why the great school at Alexandria, devoted to science and literature, was called the *Museum*.

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[16] Grove, *Dictionary of Music*, new edition, vol. ii, p. 223; Wooldridge, *Oxford History of Music*, vol. i; Parry, *Evolution of the Art of Music*, International Science Series.

(iii) *Heat*. Here again a few fundamental facts—useful in the arts—constitute the entire knowledge. They were, of course, familiar with the expansion which heat produces, say in a bladder filled with air. The three states of aggregation must have been household phenomena from the time when man began to cook his food. The properties of flame and the process of combustion were well known to blacksmiths, silversmiths, and all metal workers. Men who handled furnaces and blowpipes as the Egyptians certainly did, could not fail to acquire much information concerning the conduction of heat. Metallic tablets found in Chaldea, mummy cases and ornaments found in Egypt, all go to show that the ancients were acquainted not only with gold and silver but also with iron, copper, tin and lead. Quicksilver is not mentioned until the first century of the Christian era; nevertheless J. C. Brown, the English historian of chemistry, thinks it was known as early as 300 B.C. These metals, Au, Ag, Cu, Fe, Hg, Pb, Sn constitute the magic group of seven. A little later they acquired the following planetary symbols:

☉	Gold Sun	♀	Copper Venus	♂	Iron Mars
♃	Tin Jupiter	♄	Lead Saturn	☾	Silver The Moon
		☿	Quicksilver Mercury		

This nomenclature persisted through even to the time of Chaucer (died 1400) as will be seen from the following lines from his *Canon's Yeoman's Tale*:

> "The bodies sevene, eke lo hem here anon,
> Sol gold is, and Luna silver we threpe,
> Mars iren, Mercurie quiksilver we clepe,
> Saturnus led, and Jupiter is tin,
> And Venus coper, by my fader kin."

Heat and light must be recognized as very recondite subjects, intangible, etherial, to be comprehended later in the history of the race. It is not surprising therefore that neither Greeks nor Romans reached any valid generalization or explanation concerning the nature of heat.

(iv) As regards *Optics*, it is well known that three elements enter into every human observation involving light rays. One is the purely physical disturbance which we call light waves, another is the purely physiological question as to how the eye gives us the sensation of light, the third refers to the manner in which the brain interprets this sensation into a mental perception of light. Concerning the second and third of these problems, neither Greeks nor Romans knew even the simplest facts, but of the physical phenomena they had noted the rectilinear propagation of light, the equality of angles for incident and reflected rays, for both plane and concave surfaces, and the change of direction of a ray on entering a different medium. Ptolemy, the last original mind of the Alexandrian school, tabulates the refraction of water as follows:

Angle of Incidence:	10°	20°	30°	40°	50°	60°	70°	80°
Angle of Refraction:	8°	15°½	22°½	28°	35°	40°½	45°	50°

The rainbow, the mirage, and certain other phenomena of common life were of course as familiar to the ancients as to us.

(v) *Electricity.* Here not even the elementary facts were known. More than two thousand years were to elapse before the first electric current was observed, unless one is to speak of a lightning discharge as an electric current. A complete encyclopedia of electrical knowledge in Greek and Roman times would have included only four facts, namely, the amber phenomenon of Thales, the lightning flash, the brush discharge, known as St. Elmo's fire, and the electric eel. No one of these four facts, however, was associated with any other of the four, much less tied together by anything which might be called an electrical principle.

(vi) *Magnetism.* Information here was limited entirely to natural magnets; the attraction of lodestone for pieces of iron; the fact that magnetism acts through other bodies and cannot be isolated; also the fact of magnetic repulsion described by Pliny and Lucretius.

The art of making one magnet from another by touching or rubbing is much later. To realize how keen the popular interest in the phenomenon of magnetism was, one needs only to note the large number of synonyms employed for the word "magnet." Among them we find "Heraclean stone," "Lydian stone," "the stone," "Siderite," "Quick-iron," *ferrum vivum.*

(vii) *The nature of matter.* This brief résumé of the state of the science of physics during the Hellenistic period and a century or two later may properly close with what the Roman *intelligentia* believed concerning the constitution of matter. The two men who are responsible for these views—the two outstanding figures—are Democritus, "the Aristotle of the fifth century"—and Lucretius, his expositor. For although neither of these men reached the modern point of view concerning the atom, there is much truth in what they say. The essential difference between the ancient and modern view has been well stated by the Public Orator of Cambridge University in recently presenting Sir Joseph Thomson for an honorary degree in these words. "Immo ut Graecus ex atomo *κόσμον* eduxit, Anglus in atomum *κόσμον* introduxit."[17]

V. ROMAN SCIENCE

The contributions of Lucretius to the atomic theory

Titus Lucretius Carus is a man about whom almost nothing is known save the bare fact that he was born about 98 B.C. and died about 55 B.C.

He cannot in any true sense of the word be called the founder of the atomic theory; for he was essentially a disciple of Epicurus and Democritus, yet not an imitator of either. He is generally thought of, by the superficial student, as the man who suggested in his famous poem, *Concerning the Nature of Things* (*De Rerum Natura*) that our universe has been built up by a "fortuitous concourse of atoms."

His aim was similar to that of the Greek philosophers who preceded him and like that of the modern naturalists who have followed him; it was to unite the various branches of science into an intelligible whole, as will appear from a consideration of his atomic theory, set forth in the first two of the six books which contain his great scientific poem.

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[17] *Nature*, 105, p. 568, 1920.

(i) His initial principle is one which had, at a much earlier date, been adopted by the Eleatics, namely, that "nothing is ever begotten of nothing;" not even by divine power. A thoroughly modern statement; now more frequently expressed by saying that the phenomena of nature are subject to definite laws; or, if you prefer, miracles do not happen in laboratories.

(ii) His second proposition is that "nothing is ever annihilated, but simply dissolved into its first-bodies." This is essentially the modern doctrine of the indestructibility of matter. A little freer translation is the following: "Nature resolves each thing into its own constituent elements, and does not reduce anything to nothing." Taken together, and offered without any evidence which we should now call cogent or rigid, these first two propositions express the law of the conservation of matter; which since the time of Lavoisier has been a commonplace of physical science.

(iii) Lucretius' third statement is that "all things are not on all sides jammed together and kept in by body: there is also void in things." Here again he is following Democritus. In other words, space is only partly filled with matter. His twofold argument is as follows:

> "Wherefore, I say there is space intangible, empty, and vacant. If this were not the case, things could by no means be moved; for that which is the quality of body, namely, to obstruct and to oppose, would be present at all times, and would be exerted against all

bodies; nothing, therefore, would be able to move forward, since nothing would begin to give way."

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"That body, therefore, which is equally large with another and is evidently lighter, shows plainly that it contains a greater portion of vacuity."[18]

The reader may not be inclined to admit that there is any more "vacuity" in a hollow cylinder filled with water than in a solid cylinder of the same size, even though the solid cylinder weighs several times as much as the one containing the water. Nevertheless, experiment shows that one metal will diffuse into another and that hydrogen will pass through solid platinum or through cast iron with considerable ease. One is forced, therefore, to admit the truth of Lucretius' third contention.

(iv) He next passes to his atomic theory proper, where instead of using the Greek word *atom* to describe these minute elements of matter, he employs the Latin words *primordia*, or *semina rerum*.

His statement is as follows: "Bodies are partly first beginnings of things, partly those which are formed of a union of first beginnings."[19] This is not far from the modern phrase that bodies are made up partly of elements and partly of compounds of elements; and yet it would give an entirely false impression if by use of the word "element" one were to impute to Lucretius any conception of the modern chemical element as introduced by Boyle and Lavoisier. If these atoms, these "first beginnings of things," were not solid and indestructible, they would not permit of vacua in solid bodies, and would not stand the wear and tear of ages. Hence the inference that atoms are solid, permanent, and indivisible.

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[18] *Ideas That Have Influenced Civilization*, III, pp. 267–268.

[19] Fleming Jenkin's, *Memoirs*, I, p. 182.

(v) In addition to these properties of hardness, indivisibility, and eternal existence, the Lucretian atom possesses also perpetual motion. Matter "does not cohere inseparably massed together." "No atom," the poet says, "can ever stop giving up its motion to its neighbor."

This shrewd guess resembles strongly the ideas which Tyndall sets forth in his *Heat, a Mode of Motion.* It enables Lucretius also to explain how soft bodies, such as fruit, flesh, fluids, may be constructed out of his hard, indivisible, atoms.

The atomic doctrine of Democritus and Lucretius is made up of something like the above five theorems, arrived at, it must be remembered, without any of the evidence which we now possess from the diffusion of gases, the definite proportions of chemical combination, electrolysis, and radio-activity. A fine, brief, scholarly exposition, in English, of the views of Lucretius, not only on the atomic theory but also on the evolution of human civilization, is given by Joseph B. Pike.[20]

Heiberg[21] epitomizes the Roman science of this period as follows:

> "The Romans with their narrow, rustic, horizon, their short-sighted, practical sobriety, had always in their heart of hearts that mixture of suspicion and contempt for pure science which is still the

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[20] *Classical Journal,* 12, pp. 188–199, 1916.

[21] J. L. Heiberg, *Science and Mathematics in Classical Antiquity,* p. 80, Oxford Press, 1922. Translation by D. C. Macgregor.

mark of the half-educated—and sometimes bragged of it. Cicero,[22] the archdilettante, boasts that his countrymen, God be thanked, are not as these Greeks are, but restrict the study of mathematics to what is useful and practically applicable. So the Romans have produced no original work in these fields; what they needed they borrowed from the Greeks. They were at their worst in the exact sciences."

As minor matters, hindering the growth of physical science at the close of the Greek and Roman period, must be mentioned the absence of any gainful occupation (except astrology and magic) depending upon the principles of science, the absence of printing for the encouragement and diffusion of knowledge, and the absence of governmental protection for new ideas in the way of patent rights.

During the fourth and fifth centuries the Roman empire completely disintegrated; and the Catholic church began to assume leadership in the intellectual as well as the spiritual world. This transition period also marks a time when Greek science is drawing to its close. Another indication is the closing of the University of Athens by Justinian in 529 A.D. Affairs of the mind were ceasing to interest people. Two great names stand out in mathematics—Pappus, the geometer, and Diophantus, one of the founders of algebra, both of Alexandria and both belonging to the third century A.D. In the same group but coming a little later belong Theon, the commentator, and his brilliant daughter, Hypatia (*c.* 370–415 A.D.) who was a mistress of astronomy and mathematics and who lost her life at the hands of a Christian mob in Alexandria.

[22] *Tusc.*, i, 5.

Charles Kingsley's well known story of this name finds its foundation in her unfortunate history.

The name of Boethius (*c.* 480–524 A.D.) may be thought of as marking the close of the ancient Greek and Roman period and also as marking the beginning of the medieval period. This last great Roman philosopher was a man of profound learning, who wrote a set of widely used manuals for the four subjects which made up the quadrivium—arithmetic, music, geometry and astronomy. His outstanding work was however his *Consolations of Philosophy* which was so highly esteemed by Chaucer that he translated it into English.

Along with Boethius ought to be mentioned Cassiodorus (*c.* 490–585 A.D.) a Roman counselor who, in his leisure moments left over from collecting knowledge and writing books, used to amuse himself with the manufacture of sun-dials and water-clocks.

CHAPTER III

ARABIAN PHYSCIS

> "Was du ererbt von deinen Vätern hast,
> Erwirb es, um es zu besitzen."
> —*Faust* 682–683.

In less than a century after the invasion by the Huns (375 A.D.) the western branch of the Roman Empire (which Theodosius the Great had divided between his two sons in 395), was conquered by German mercenaries under the leadership of Odoacer. The defeat of the last western emperor, Romulus Augustulus, by Odoacer was in 476; and for three centuries following, i.e., up to the time of Charlemagne, nothing worthy of mention was done either in science or literature. Greek culture had long before been discouraged by the Christian Fathers as being "pagan" and hence "false." Greek views of the figure of the earth and of the motions of the planets were especially obnoxious.

Only a few years previous to this time the bishop of Rome had been declared by the Roman Emperor in the West to be supreme in ecclesiastical power; and the long line of powerful popes was initiated. When Gregory the Great (c. 540–604) was chosen pope in 590, he shortly showed himself a wise statesman and took over the government of the city of Rome which remained in the hands of the papacy from that day until the year 1870. It is an interesting coincidence that just as the temporal power of the Christian church was beginning on the northern shores of the Mediterranean there was about to arise on the southern side of this sea another and a new religion which was to become a great rival of Christianity and to grow in worldly power at a rate which is without precedent. For it was in the year 570 A.D. that Mohammed was born; and he was therefore a contemporary of Gregory the Great. At the age of fifty-one, i.e., in the year 622, of our era, Mohammed in order to escape certain enemies, suddenly changed his residence from Mecca to Medina. Ten years later Mohammed died; and his followers proceeded to collect several series of revelations—pretended revelations—which were later assembled into a volume called the *Koran* possibly the most widely read book in the world.

ARABIAN CULTURE

Mohammed's successors called themselves Caliphs and had remarkable success in conquering all the neighboring countries, Syria, Persia, and Egypt. By the first decade of the eighth century (708 A.D.) the Arabs had under their control all the northern shore of Africa; in the following decade they were complete masters of the Spanish peninsula; by 752 they had established the Emirate of Cordova a real Empire in the West, independent of the caliphate in Bagdad. In fact their northern sweep was unchecked until they met the heavily armed horsemen of Charles Martel in 732, at the battle of Tours. Accordingly it will be seen that by the time Charlemagne (crowned emperor of the Romans in 800; died in 814) had established the Holy Roman Empire, the Moslems had extended their control from Mesopotamia to Spain. Along the shores of the Mediterranean only France, Italy and Greece remained outside the Moslem power; and everything in the way of Greek, Roman or Christian culture was, of course, the subject of Moslem attack. At this period the three great centers of culture were Alexandria, Rome and Constantinople. The first of these cities was captured by the Arabs in 640; but Constantinople withstood them for eight centuries and Rome has never yielded to them. There can be no doubt about the virility of the people who were led by the caliphs. Among them were a great variety of Semitic nations; in fact they formed the southern front of what historians tell us is the greatest line of battle ever drawn, namely, the fight between the great white race—the Indo-Europeans—on the north and the Semitic races—Arabs, Phoenicians, Hebrews, Carthagenians—on the south. For many centuries these two contending lines have faced each other across the Tigris and Euphrates or across the Mediterranean. The Indo-Europeans, represented by the Greeks, Romans, French, Spaniards and Germans, have been victorious; but victory has not been easy. In the particular phase of battle which we are now considering, the left wing of the southern army was not driven out of Spain until the year when Columbus discovered America and Ferdinand and Isabella captured Granada—the last stronghold of the Moors.

It is not surprising that among such vigorous races there should be found men of intellectual power with a curiosity to know the best that had been thought and done in the world. Others among them were doubtless eager—

as every wise man is—to know what it is that leads his opponent to think as he does. At any rate, the Arabs began to exhibit an especial interest in medicine and astronomy. First of all they translated into Arabic the works of Hippocrates (born 460 B.C.), Theophrastus (born *c.* 372 B.C.), the successor of Aristotle, and Galen (born 130 A.D.) Later they translated Aristotle, Euclid, and Ptolemy. These are some of the books which in still later centuries were retranslated into certain European languages and were thus saved to posterity. During the long years of medieval times, the Arabs placed "in cold storage," as Professor Lynn Thorndike says, a large amount of learning; some of it in western seats of learning such as Cordova and Seville, some in eastern cities such as Jerusalem and Bagdad. Meanwhile Constantinople remained, for more than a thousand years, a Greek city and the capital of the eastern church. Here also was collected much of the best that had been thought and said by the Greeks. When the genial intellectual climate of the Italian renaissance set in, many of these store houses, Moslem and Christian, became treasure houses to scholars from western Europe.

ARABIAN CONTRIBUTIONS TO PHYSICS

At the very outset it must be confessed that the debt of modern physics to the Arab is distressingly small. Some of the other sciences owe them more than does physics. Among the items of indebtedness the following must, however, always have an interest for the student of the history of physical science.

(i) One distinct service of Arabian scholars was the introduction of the so-called Arabic—really Hindu—numerals into western Europe. The new arithmetic was presented to the western world in various forms, at different places and at different times; but the earliest introduction of any importance which we possess is that of Al-Khowarizmi, a Persian, who flourished about 825 A.D. and worked in the library of the Caliph Al-Mamun. His work has been preserved in a twelfth century translation into Latin by Robert of Chester; and this translation has recently been turned into English, edited and published in a manner worthy of its importance by Professor L. C. Karpinski.[1] For six or seven centuries following its first appearance this treatise was copied, quoted, and commented upon in Italy, Germany, France and England.

Another influential man in the introduction of the Hindu system was Al Biruni (died *c.* 1038), an Arab living in northwest India and distinguished as a geographer. In his description of India, he calls attention to the fact that the inhabitants of that country differ from all the rest of the world in using different symbols for each number and making the value of each symbol depend quite as much upon its position as upon its form. The nine digits and the zero thus go to make up what mathematicians call the positional decimal system. However the word *decimal* must not here be allowed to suggest *decimal fractions;* for they do not make their appearance until near the end of the 16th century. The beautiful simplicity of this Hindu system of reckoning which the Arabs handed over to western Europe, and its aid to clear thinking is something never to be forgotten. The Greeks and Romans had been severely limited by their clumsy method, which was practically a system of straight marks except for the V, X, L, C, and M. Position played a not very important rôle; the simplest operations of multiplication and division were bewilderingly complex.

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[1] *Robert of Chester's Latin Translation of the Algebra of Al-Khowarizmi*, Macmillan, 1915.

The transmission of the Hindu system through the Arabians to western Europe is a long, complicated and, at points, very uncertain story. In the diffusion (as distinguished from the introduction) of this important knowledge it is, however, generally agreed that Leonardo of Pisa, who published his great work *Liber Abaci* in 1202, is the outstanding figure. Professor H. B. Fine speaks of this book as "a remarkable presentation of the arithmetic and algebra of the Arabians which remained for centuries the fund from which reckoners and algebraists drew, and is, indeed, the foundation of the modern science."[2]

The upshot of the whole matter is that about the time of the Norman Conquest, or shortly thereafter, the European nations had placed in their hands an elementary treatise on analysis in which Al-Khowarizmi sets forth the accumulated results of a thousand years' study of numerical relations, powers of numbers, and equations of the first and second degrees.

The next great step in mathematics—the invention of logarithms—had of course not yet been taken, nor had any symbol for equality yet been invented; nevertheless from here on the observer and the experimentalist has at his disposal a process quite free from the method of synthetic geometry—a process which, in physics, was to reach a development so high that Lagrange in his *Mécanique Analytique* exultingly remarks, "One will find no figures in this work."

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[2] *The Number-System of Algebra*, p. 112.

To the Arabs we also owe the introduction of the sine instead of the chord used by the Greeks. The use of this function saves the continual doubling of the angle and afterwards dividing by two. The cosine came something like a hundred years later than the sine.

(ii) The Julian calendar year, it will be recalled, is exactly 365^d6^h. The divergence between this and the tropical year was all the while making the exact determination of this latter period highly desirable; and it is to Albatenius (850–929), an Arabian astronomer, that we owe the first correction to the tropical year of Ptolemy. The modern value—what we, at present, modestly call the true value—is $365^d\ 5^h\ 48^m\ 46^s$. Albatenius, a thousand years ago, made it $365^d\ 5^h\ 46^m\ 22^s$. He was easily first among all the Arabian astronomers. In addition to this, he corrected the hitherto accepted value of the precession of the equinoxes, arriving at the value 55 seconds. The birthplace of Albatenius was in Mesopotamia; but he died in Syria, of which province he was governor.

(iii) In the domain of optics, the Arabs made distinct advances without, however, making any contribution which can be called outstanding. Their best work is probably contained in Alhazen's *Treasury of Optics*, first printed at Basel in 1572. The author is supposed to have been born at Basra, some 50 miles from the shore of the Persian Gulf and to have died in 1038 at Cairo. His life, however, was largely spent in Spain.

The *Treasury of Optics,* in its first book, discards the Euclidian notion of vision, namely, that the eye emits light which goes forth to examine and report upon the object. The author then proceeds to give the structure of the eye as he had learned it from the anatomical writings of his day.

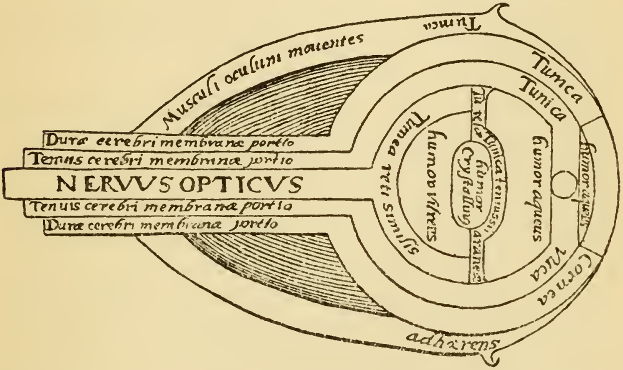

FIG. 1. CROSS-SECTION OF THE HUMAN EYE ACCORDING TO ALHAZEN

The accompanying figure was drawn by Risner from directions laid down by Alhazen; and first appeared in the Basel edition of 1572. Here one finds that Alhazen gives the three refractive media of the eye—the aqueous humor, the vitreous humor, and the crystalline lens—practically as we know them today. In addition to this he distinguishes four different membranes, namely, the cornea, the uvea, (so called because it looks like a black grape skin, *uva*, and now known as the choroid coat), the retina, and the sclerotic.

In Books 4, 5, and 6 of his *Optics*, Alhazen extends the laws of reflection at plane surfaces to three different forms of curved mirrors, spherical, cylindrical and conical. In the seventh book he comes very near to, but yet misses, the discovery of the true law of refraction. He, at least, points out the mistake of Ptolemy's view that the ratio between the angle of incidence and the angle of refraction is a constant, and discovers that the refracted and incident rays both lie in a single plane containing the normal to the refracting surface.

The modern solution of the problem of the increased size of the moon when seen on the horizon is also to be found in this seventh book. The explanation is, of course, that the eye has an impression of distance greater in the direction of the horizon (on account of many objects lying in the line of sight) than in the direction of the zenith.

The magnifying power of a segment of a glass sphere appears also to have been observed by Alhazen,[3] a trifling fact in itself perhaps; but one of a series of observations which probably led up to the use of spectacles. Aristophanes (455–375 B.C.) has one of his characters delete certain figures (in an account recorded on a wax tablet) by use of a burning glass. A plano-convex lens has been found in Pompeii; and a biconvex lens has been discovered among Roman ruins in England.

(iv) The science of mechanics owes not a great deal to the Arabs; nevertheless the series of specific weights determined by Al Khazini (1137) must be reckoned as distinctly helpful. His measurements cover most of the then known metals, six or seven kinds of crystals and ten different liquids with an average accuracy of about one per cent.

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[3] *Opticae thesaurus*, vii, 48.

When one considers the semi-barbarous condition from which the Moslem nations arose and the semi-barbarous state into which they lapsed shortly after the fourteenth century, the results which they achieved in science must be estimated as one of the remarkable and striking facts in human history. The question is at once raised as to whether there is a certain virility which goes with the open-air life of plainsmen and which fits them, when once they set their minds to it, to become the masters of the intellectual world. The evidence points to a negative answer. All that we know about these individual Moslem scholars indicates that they were men acquainted with leisure, familiar with libraries, and trained in such important centers of learning as Bagdad, Damascus, Jerusalem, Seville and Cordova. Many of the men who did the actual work were Greeks, Persians, Jews and Copts employed by Arabs. Compared with the people living on the northern shore of the Mediterranean, the educated Arab was probably less of a slave to scholasticism and superstition and was thus unconsciously impelled to translate and place "in cold storage," for later generations, a great body of ancient learning.

CHAPTER IV

PHYSICS IN THE MIDDLE AGES—SCIENCE IN THE HANDS OF THE CLERGY

> "Sciences and Arts are not cast in a mold, but rather by little and little formed and shaped by often handling and polishing them over; even as beares fashion their yong whelps by often licking them."
>
> —MONTAIGNE, *Essays*, Book II, Chapter 12.

We have now considered one phase of physics in the Middle Ages, and before passing to the development of physics during the latter part of this period, it may be well to turn for a moment and glance backward. One not infrequently meets the view that the dark ages preceding the thirteenth century were a period of complete stagnation, during which little or no progress of any kind was made. How far this is from the truth will be realized by a consideration of the following excellent picture of the western world at the end of this period, drawn by Professor James Harvey Robinson with only seven strokes of the brush. We are breaking medieval time into two periods. Robinson's picture of what had been accomplished during the first of these periods and the state of affairs at the beginning of the second is as follows:

(i) "A group of national states in which a distinct feeling of nationality was developing had taken the place of the Roman empire."* * *

(ii) "The church had in a way taken the place of the Roman Empire by holding the various peoples of western Europe together under the headship of the pope and by assuming the powers of government during the period when the feudal lords were too weak to secure order and justice." * * *

(iii) "A new social class had come into prominence alongside the clergy and the knightly aristocracy. The emancipation of the serfs, the founding of towns, and the growth of commerce made it possible for merchants and successful artisans to rise to importance and become influential through their wealth. From these beginnings the great intelligent and educated public of modern times has sprung."

(iv) "The various modern languages began to be used in writing books." * * *

(v) "Scholars began as early as the year 1100 to gather eagerly about masters who lectured upon the Roman and Canon law or upon logic, philosophy or theology." * * *

(vi) "Scholars could not satisfy themselves permanently with the works of Aristotle, but began themselves to add to the fund of human knowledge." * * *

(vii) "The developing appreciation of the beautiful is attested by the skill and taste expressed in the magnificent churches of the 12th and 13th centuries which were not a revival of any ancient style but the original production of the architects and sculptors of the period."[1]

From this time on, one finds physics developing in the hands of men from western Europe. Physical science, like nearly every other intellectual interest at that time, was largely in the control of the church. The seven liberal arts which had come down from Roman time and which may be traced back even to Plato, covered nearly the whole range of medieval learning. In advance of the liberal arts there were only the two laws (civil and canon), and medicine. *Grammar* was studied in order to know the language of the church which was Latin; *rhetoric* and *logic* in order to use this language effectively. The chief use for *arithmetic* was found in problems associated with discreet numbers and mystic numbers; *geometry*, with continuous quantity; most of the *music* was church-music and had to do with melody, a succession of pleasing ratios. Music is, therefore, employed in a much narrower sense than that in which the Greeks used it. *Astronomy* enabled one to establish the church calendar. In this scheme of seven topics which made up the trivium and the quadrivium it will be observed that neither chemistry, geology nor physics found any place. These sciences had not yet crystallized. When one finds the word *physica*—St. Hildegard (1098–1179) wrote a book with this title—it denotes the broad science of nature and is more nearly what we now call natural history than physics; *physica* deals with plants and animals; *physics*, with energy and inanimate matter.

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[1] *History of Western Europe*, pp. 274–276.

This second part of the medieval period which we are about to consider is marked by three noteworthy revolts; the opening of the period coincides with the literary renaissance; the middle, with the Reformation or religious renaissance; while the close of the period leads one up to, but not into, the beginning of modern science or, if the reader pleases, the scientific renaissance.

Dante (1265–1321), whose birth antedates that of Galileo by an even three hundred years save one, and who was one of the very first to throw aside Latin and write in the vulgar tongue was medieval in outlook and in interest; yet he must be considered as having prepared the way for the first renaissance. The sympathy which this greatest of Italian poets felt for science and scholarship is evinced by the fact that in his *Divine Comedy*, "only one pope is placed in Paradise and that one not on account of his office but rather on account of his scholarship."[2]

Petrarch (1304–1374) and Boccaccio (1313–1375)—each of whom has been called "the first of modern men"—also belong to this time.

If it is desired to identify the religious renaissance with a single date one may perhaps choose the year 1521, when Luther made his dramatic defense before the diet of Worms.

The initiation of modern science means getting free from the trammels of authority and adopting independent experiment as a means of acquiring knowledge. This freedom came much later and its beginning may perhaps be identified roughly with the year 1600, in which Giordano Bruno (1548–1600) was burned at the stake in Rome because he wanted to see the world unclouded by authority and tradition.

SCHOLASTICISM

So much by way of characterization of the period upon which we are about to enter. During the whole of the period there prevailed a mode of thought known as scholasticism; and this system of logic is so frequently mentioned in the literature of science that we must linger a moment to consider just what is meant by it.

In 787 Charlemagne decreed that a school should be established in connection with every abbey in his domain.

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[2] A. de Salvio, *Romanic Review*, **11**, p. 262, 1920.

These church schools a little later became the centers of medieval learning and marked the rise of a new intellectual interest, in addition to faith and superstituon which had hitherto controlled the church. This lure of knowledge led men to seek not merely what they should believe, but also to discover what was true, or at least what was reasonable. And in order to justify and defend those dogmas which the church asked men to accept on faith, the teachers in these church schools, founded by Charlemagne at St. Denis, Lyons, Orleans, Tours, St. Gall, and other places, set about to create a suitable logic. This logic—this dialectic—being a product of these schools, was given the name of *scholasticism*. These schoolmen found their logic among the Greeks and only among the Greeks. They became, as has been well said, philosophers *ad hoc;* not free and independent thinkers such as the Greek philosophers were, but logicians and dialecticians whose one aim in life was to establish Christian dogma on a logical basis, to give to the belief of the church an intellectual foundation.

These efforts, this method, and this attitude of mind, are what is meant by scholasticism. This mode of thought controlled things from the ninth to the fifteenth centuries. Thomas Aquinas (1227–1274), a Dominican, may be considered as the typical and leading scholastic spirit.

Now as a matter of fact it turned out that these cloister schools which became acquainted with Aristotle's logic, also became acquainted with his science; and although this knowledge of Aristotle came to be widely spread about the thirteenth century, the church took the matter very complacently, and winked at this peripatetic science on the ground that it could do no harm. Any body of science that had been subordinated to the authority of the church was harmless. The thing that was feared was an original or inquisitive science that should put nature on the witness stand and defy the authority of the church.

Accordingly the science of Aristotle became so fashionable that for two hundred years after the thirteenth century, one could not take honors at the great Christian universities of Bologna, Naples, Padua, Paris, or Oxford, unless he had proved himself proficient in his Aristotle. The object of scholasticism was thus very far from being a study of nature; it was in fact a study of authorities, and came very near being a study of Aristotle.

We have now to consider some of those rare minds who had the wit and courage to break away from scholasticism and think their own thoughts. The question which here immediately concerns us is what happened in physics during the three centuries between the birth of Dante, 1265 and the birth of Galileo, 1564.

MEDIEVAL MECHANICS

Albert the Great and Roger Bacon

Let us first of all follow the development of mechanics, the principles of which have proved so fundamental to all the other branches of physics. It will be generally admitted, I think, that the two outstanding figures in science during the thirteenth century were Albertus Magnus (1206–1280) and Roger Bacon (1214–1294). Like most other leading men of that century, they each belonged to one of the religious orders; Albert was a

Dominican, Bacon a Franciscan; Albert was orthodox, Bacon was heterodox; Albert received preferment whereever he went, Bacon spent fourteen years in prison because his remarks about the ignorance of the clergy were *not* acceptable to the general of his order. Both were men of wide training and comprehensive learning. Albert was educated first at Padua, then at Bologna, Bacon at Oxford and Paris; Albert's works were recently published at Paris in thirty-six volumes; Bacon's works are spoken of by Whewell as at once the Encyclopedia and Organum of the thirteenth century. Albert was in close touch with all the science of the ages which preceded his own, Bacon was master of the best scientific method of his own time, as is evident from his ideas of matter and force as well as from his summary of the causes of error. Among these latter he includes authority, custom, the opinion of the unskilled many and the concealment of real ignorance with the pretence of knowledge. It might be expected that some real advance in the subject of mechanics would have been achieved by one or the other of these able minds; but such does not appear to be the case. We owe much to Bacon; we are grateful for his attitude of mind, for his emphasis on language and mathematics as studies preparatory to any serious work, for his insistence upon observation as an essential means of knowledge, and for his independence of Aristotle with whom he was well acquainted. On the other hand, we owe to Bacon no important contributions to knowledge and his work in physics has been too often overrated. Many have gone so far as to credit him with having instituted the experimental method of studying physics. The observant reader will discover, however, that when Bacon uses the word "experiment" he means by it more nearly what we understand by experience and observation, not some result obtained from prearranged apparatus and circumstances. The only experimenters of this period appear to have been the alchemists. A profound student of this period, Professor Lynn Thorndike, puts the matter as follows:

> "It is, however, significant that 'experimental science' is the last of the natural sciences discussed by Bacon. As we read his praises of it, we see that he is not so much thinking of an inductive method through regulated and purposive experience and observation to the discovery of truth—altho' his discussion of the rainbow is an example of this—as he is thinking of applied science which puts to the test of practical utility the results of the 'speculative' natural sciences and is thus not, like modern experimentation, the source, but the 'goal of all speculation'."[3]

More must be said about Bacon's work when we come to the consideration of medieval optics; but even here it is to be borne in mind that burning glasses and spectacles were common in his time and there is no evidence that he ever made the telescope with which he is sometimes credited.

A long drab period of nearly two centuries now intervenes, during which no outstanding advances in mechanics were made; but at the end of this period appears a mind of the first order, a man who was in his prime—forty years of age—when Columbus discovered America.

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[3] *American Historical Review,* 21, p. 474, 1916.

Leonardo da Vinci, 1452–1519

It is a remarkable fact that this wonderful Italian never published anything during his lifetime. His all-capable mind was, however, incessantly at work upon an enormous number of subjects. His notebooks are filled with the results of his studies in painting, drawing, statics, dynamics, hydraulics, geometry and human anatomy. From those of his manuscripts which have been published, it is clear that Leonardo had a good working knowledge of the lever, of the inclined plane, of the principle of moments, of the different types of equilibrium (stable, neutral and unstable) and a fairly good grasp of the principle of virtual velocities. He and Cardan (1501–1576) were each convinced of the impossibility of perpetual motion by any ordinary mechanical means; but their ideas of force were still those of Aristotle. The mechanics of Leonardo da Vinci, Cardan and some of their contemporaries represents the mechanics of the sixteenth century which was essentially statics, no approach having yet been made to the principles of kinetics.

The work of these men has been viewed from two different standpoints; one view is that of the eminent French chemist, physicist and historian, Duhem, who maintains that:

> "Il n'est, dans l'oeuvre mécanique de Leonard de Vinci, aucune "idée essentielle qui ne soit issue des écrits des géometres du moyen "âge et, particulièrement, du traité de ce grand mécanicien qui nous "avons nommé le Précurseur de Leonard."[4]

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[4] *Les Origines de la Statique,* I, p. 192.

This precursor of Leonardo is the unknown author of a manuscript in the Bibliothèque Nationale at Paris (fonds latin, No. 7378-A) in which Duhem finds the germs of practically all the ideas of everything that was done in mechanics from the thirteenth century (to which period the manuscript belongs) up to the beginning of modern dynamics in the first half of the seventeenth century.

The other point of view is that all these mechanical ideas were decidedly hazy in the thirteenth century and remained so until the sixteenth century when they were somewhat sharpened up by Leonardo, Cardan, Tartaglia, Benedetti and Stevin, each of whom made some distinct and original contribution.

The exact language, precise definition and clear formulation which always accompanies a complete grasp of any dynamical principle is never found until the seventeenth century; but so many concrete and particular cases are mentioned that there can be little or no doubt that the essential facts were being cleared up by one man after another; and one hesitates to think that this was all done by "theft" and "plagiarism"—harsh words which appear frequently in Duhem's pages. It is not an easy matter to make sure that any particular manuscript or book came under the eyes of a man who worked some four centuries ago, especially when he himself says little or nothing about his sources. Nor is it to be forgotten that an absolutely new idea is one of the rarest things in the world. Much that we reckon as fine work is merely a new combination and formulation of what has already been done, the discovery of new relations between long known facts, or the assimilation of the work of others.

On the other hand one of my colleagues in history reminds me that ethical responsibility in quoting authority is of recent date.

We come now to consider some of the contributions of Leonardo's immediate successors.

J. Cardan, 1501–1576

The work of this well known Italian need not long detain us; for his best results are purely mathematical. In mechanics he announced a law of the inclined plane as follows: *The force required to hold a body at rest on a frictionless plane is proportional to the angle which the plane makes with the horizontal.* A very simple experiment would have shown him his error; but experiments were not fashionable—not even good form—during the sixteenth century. His great work *De subtilitate rerum* (Leyden, 1551), represents, however, the best physical learning of his time. Here will be found his account of "Cardan's suspension" so widely used in connection with the mariner's compass; although the device is one which Cardan does not claim as his own. He was a man of wide training—educated at Pavia and Padua—a physician, an astrologer, a philosopher and a mathematician. Concerning his personal character critics are divided; those who know the circumstances of his up-bringing will be inclined to be generous.

Niccolo Tartaglia, 1506–1559

Tartaglia was another brilliant product of northern Italy, a contemporary of Christopher Columbus, born at

Brescia. At six he was fatherless and while still a lad, was terribly beaten and disfigured by French soldiers. He lived, as some one has said, "with a single companion, a daughter of Poverty, named Industry." His great work *La Nova Scientia* was published at the age of thirty-one. Its place in the history of physics will perhaps be cleared up by remembering that the idea of force took its rise from a study of falling bodies. Aristotle, as is well known, classified motions, by dividing them into two groups, "violent" and "natural"—a nomenclature which persisted for two thousand years. About this classification as a frame work had been built a structure of axioms, definitions and theorems, quite without any foundation of accurate observation, experiment, or measures, forming a system of paper mechanics, which reached its fullest development perhaps in Tartaglia's *New Science* a treatise on gunnery which appeared in Venice in 1537.

It was just at this time when stone ammunition for artillery was being replaced by iron. The popular siege gun of the day was a very short mortar. The path of a projectile was recognized as the path of a falling body. The laws of falling bodies were acquiring human interest in proportion as men learned to cast larger and better guns.

For a summary of the laws of motion as they were conceived of—imagined, not demonstrated—in medieval times the following seven characteristic propositions enunciated by Tartaglia will serve.

Book I

Proposition I

"Every heavy body, in natural motion, moves more and more rapidly after leaving its starting point, or on approaching its terminal point.

Proposition II

"All similar and equal heavy bodies begin their natural motions with equal velocities; but those which traverse longer paths reach their terminal points with higher speeds.

Proposition III

"Every heavy body, in violent motion, moves more and more slowly after leaving its initial point and on approaching its terminal point.

Proposition IV

"All similar and equal heavy bodies reach the end of their violent motions with the same speed; but at the beginning of such [violent] motions those bodies which have the longer path to traverse depart with the greater speed.

Proposition V

"No heavy body is able to move during any length of time, or over any distance, with a motion which is a mixture of natural and violent motion."

Book II

Proposition VIII

"When similar and equal heavy bodies are projected with the same force, at different angles of elevation above the horizontal plane, the one whose path has an elevation of 45 degrees will have the greatest range.

Proposition IX

"When two similar and equal heavy bodies are projected with the same moving force, the one at an elevation of 45 degrees, the other in a

> horizontal direction, the straight part of the path of the one which was elevated at 45 degrees is about four times as long as the straight part of the path of the other."[5]

It will be observed that, with a single exception, these propositions are either indefinite or inaccurate or both; but they are evidence that considerable interest was being taken in these subjects. The statement that an elevation of 45° gives the maximum range is a combination of happy intuition and correct observation. The truth of this theorem Tartaglia inferred from the fact that a shot fired vertically into the air has zero range, and likewise one that is fired horizontally. Halfway between these two, he concluded, must be the angle which gives the maximum range. In spite of this correct conclusion, Tartaglia must for the present be reckoned among the Aristotelians.

In 1546, nine years after the publication of his first book on projectiles, Tartaglia published a second volume (*Quesiti et Inventioni diverse*) largely devoted to military tactics, munitions, and ballistics.

In the meantime, his views had undergone a radical change; there is no longer any mention of "violent" and "natural" motions; the possibility of a mixture of these two types of motion, which was denied in Book I, Proposition V, of his earlier treatment, is now tacitly assumed. The following extracts (Book I, Quesito terzo) are typical:

> "The higher the angle of fire the less the curvature of path; but no part of this path is ever perfectly straight except in the two directions above mentioned, namely directly upwards toward the

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[5] *Nova Scientia*, pp. 1–18.

heavens, or directly downwards toward the center of the earth; because in every direction, except these two, there is always some part of gravity drawing the shot out of its line of motion."* * * "This will be easily understood, without any long demonstration, from the accompanying figure as well for shots directed below the horizon as for those directed above it.

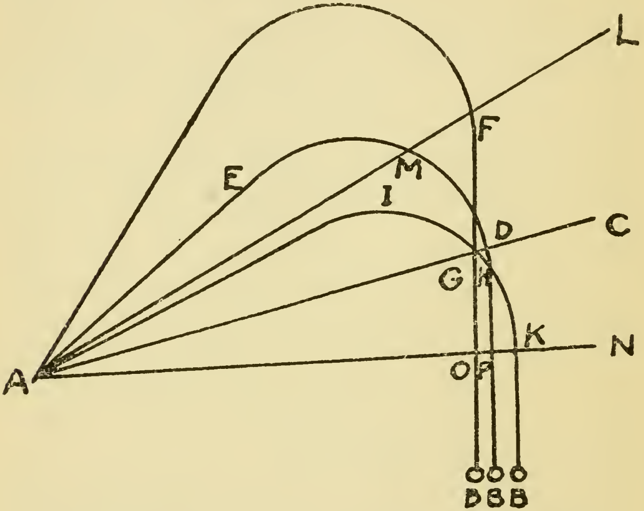

FIG. 2. THE TRAJECTORY OF A CANNON BALL ACCORDING TO TARTAGLIA

"Whence it will be manifest that, in no other direction than the two mentioned, will a shot have any least part of its path along a perfectly straight line.

Figure 2, which is a fac-simile of Tartaglia's will illustrate his meaning and will show that he quite comprehended the fact that gravity acts upon a cannon ball

all the while. He now occupied a position far in advance of the peripatetic school and was indeed not far from understanding the composition of motions.

J. B. Benedetti, 1530–1590

A much more energetic critic of Aristotle was Benedetti, who published a treatise on *Mechanics* (*De Mechanicis*) at Turin in 1585, about the time Shakespeare was just beginning to write. Here he handles both Aristotle and Tartaglia without gloves.

Benedetti's work is contained in a volume of six essays which he calls *Diversarum speculationum Liber.* It was critical rather than constructive; but this was precisely what was needed at that time when authority was in the saddle where observation and experiment and mathematics rightly belong.

In one of these six essays which he calls *Disputationes*, Benedetti discusses the peripatetic notion of falling bodies. The following extract serves not merely to illustrate his style, but also sets forth an important contribution to dynamics, namely, the suggestion that the cause of motion is contained within the body itself, and does not reside in the air or in some spot on the earth's surface where the body is about to come to rest.

Discussion of Certain Notions of Aristotle; Chapter XXIV

"Aristotle, at the close of his eighth book on Physics, expresses the opinion that a body once set in motion by force, and then separated from its source of motion, keeps on moving because the motion is sustained by the surrounding air or water. But this cannot be; since, on the contrary, the air which rushes into the place vacated by the body, in order to destroy the vacuum, not only does not push the body ahead, but rather hinders it from moving, since the air is forcibly conducted to the rear of the body and separated from the anterior portion of the body, and thus offers resistance [to the body]; furthermore, in proportion as the air in said parts is condensed, it is in the same proportion rarified in the posterior portion, where, rarifying itself by force, it does not permit the said body to move with that speed, with which it, itself, flees, because every agent, in acting, suffers [some diminution].

"Hence when the air is attacked by this body, the body itself is also attacked by the air.

"Thus the rarefaction of the air is not natural, but violent, and, on this account, resists and closes up; but what's more, nature does not allow a vacuum to open up between any two of the said bodies. Therefore these are always close together and a body in motion, while unable to part company with the air, has its own speed reduced.

"Thus, therefore, the speed of a body, once separated from its original source of motion, takes its rise in a certain natural pressure coming from the impulse received by the said moving body.

"This pressure and this impulse, in the case of natural and rectilinear motion, necessarily increases, since the body has always, within itself, the cause of motion, i.e., a tendency to travel toward the place assigned to it by nature.

"Aristotle, in *De Coelo*, Book I, Chapter 8, ought not to say that the speed of a body increases in proportion as it approaches its terminal point, but rather that its speed grows in proportion as it recedes from the initial point; because the longer the body continues in natural motion, all the while receiving a fresh impulse, the greater will be this pressure; and because the body contains within itself the cause of motion, namely, an inclination to seek its proper place, out of which it will not move into a new position except by force.

"Nor is Aristotle correct in Book VIII, Chapter 9, of his *Physics* and Book I, Chapter 2, *De Coelo*, when he describes any motion, in general, as being compounded of rectilinear and circular motions—something which is quite impossible."[6]

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[6] *Diversarum Speculationum*, p. 184, Taurini, 1585.

So saturated however was Benedetti with the prevailing views of his time that he was unable to throw them all off. He still believed that bodies of the same size and shape fall with speeds which are proportional to their densities.

Benedetti has been credited with giving us the definition of *moment of force* in its modern sense; and, indeed, he makes it very clear, in Chapter III of his *De Mechanicis*, that he thoroughly understands the two factors which enter into every torque, namely, the force and the perpendicular distance from the axis of rotation. The statements of Benedetti are much more explicit than those of Leonardo da Vinci, which the reader will find set forth in English on pages 109–113 of Hart's *Mechanical Investigations of Leonardo da Vinci;* but it may be fairly doubted whether *either* of these men ever thought of the product of, *lever arm* × *force*, as constituting a single quantity, in the manner in which the modern student early learns to think of torque; and probably much less did they think of it as a directed quantity.

This is a typical example of the slow and gradual development of ideas, definitions, principles, and instruments which to the present generation appear surpassingly simple.

Benedetti also makes it very clear that he has more than a faint adumbration of what we now call Newton's First Law of Motion. Speaking of a stone whirled in a sling, he points out[7] that the more rapidly the stone is whirled the stronger the pull on the string and then adds "*quodvis*

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[7] *Diversarum Speculationum*, p. 287.

grave corpus, aut per naturam aut per vim motum, rectitudinem itineris naturaliter appetit." This statement shows that he had grasped the idea of motion in a straight line being the "natural" one, but had not yet reached the conception of this motion being uniform, and still farther was he from the simple algebraic expression in which Galileo describes the motion of a body left to itself, namely, *Momentum = constant.* The accompanying figure in which Benedetti represents a stone, *a b*, being released from a sling, *e a*, and moving off, not along the radius, but along a tangent to the circle, shows a rather intimate acquaintance with the facts described by Newton's First Law.

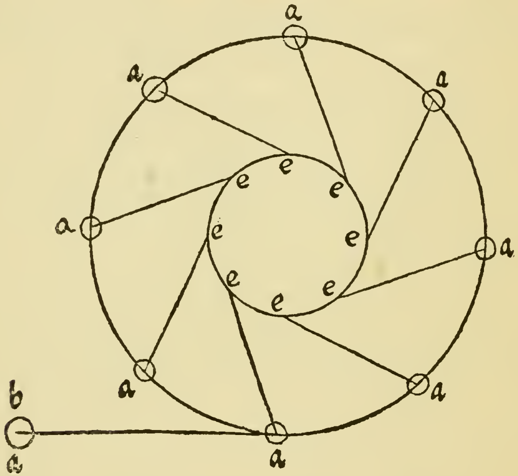

FIG. 3. BENEDETTI'S APPROXIMATION TO THE FIRST LAW OF MOTION

Another problem of interest upon which Benedetti broke a lance is the classical one of a ball allowed to fall from the surface of the earth into a cylindrical hole bored through the center of the earth. Here again, as all through his work, he is correcting the error of Aristotle and his commentators who maintained that the ball would fall to the center—its "natural place"—and there stop. Benedetti points out (pp. 368–369) that on the contrary the ball would oscillate up and down along a diameter of the earth just as if it were attached to the lower end of a very long string, the upper end of the string being fixed; in other words the motion would be that of the bob at the end of a very long pendulum, a motion which we now call *simple harmonic.* Far away as this statement is from the quantitative law of a freely falling body, it illustrates nevertheless the slow and gradual evolution of this law. This particular problem is one which has been considered by many later dynamists.[8]

F. Commandino, 1509–1575

The rôle of good nomenclature in hastening the development of any science is not to be despised. Among the many translators of the sixteenth century—the age of translations—was the Italian scholar who translated from the Greek the work of Archimedes. The word ῥοπή meaning "the weight which turns the balance," Commandino rendered "moment of force" and attached this name to the product of the weight by the arm through which it acts. From here on the first law of statics runs as follows: a lever is in equilibrium only when the two moments of force acting upon it are equal and opposite. Commandino's important work on *Centers of Gravity of Solid Bodies* was published in 1565 when Shakespeare was only a year old.

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[8] See, for example, Euler's *Letters to a German Princess,* vol. I, Letter 49.

Simon Stevin, 1548–1620

The first man to establish in a thoroughly satisfactory manner the second great principle of statics—that of the inclined plane—was Simon Stevin who is an interesting character if for no other reason than that he represents the very highest attainments in mechanics when limited to statics alone. He is indeed the last great representative of the school of Archimedes.

Stevin was born at Bruges, nine miles from Zeebrugge on the North Sea, the port of Flanders immortalized by Captain Carpenter of H. M. S. "Invincible" in April of 1918. Stevin's death occurred in the same year in which the Pilgrim Fathers landed; accordingly his work was finished long before Galileo's dynamical ideas were published.

His principal contribution to mechanics is his new and highly original proof of the parallelogram of forces. Stevin's surpassingly simple and convincing method is to take a triangular prism such as that represented in section by ABC in figure 4. The base of the prism, *A-C*, is horizontal. An endless chain is now thrown over the prism as indicated in the figure. Evidently such a chain will be in equilibrium, even when there is not the slightest friction involved. If it were not we should have already realized perpetual motion and an exception to the law of the conservation of energy; but since the chain is in equilibrium, one may remove the lower part, which hangs symmetrically between the points *A* and *C* without disturbing this equilibrium. Consequently the portion of the chain *A-B* must just balance the portion *B-C:* and since the weights of these portions are to each other as their lengths, it follows that, for *inclined planes having the same altitude any given force along the plane will sus-*

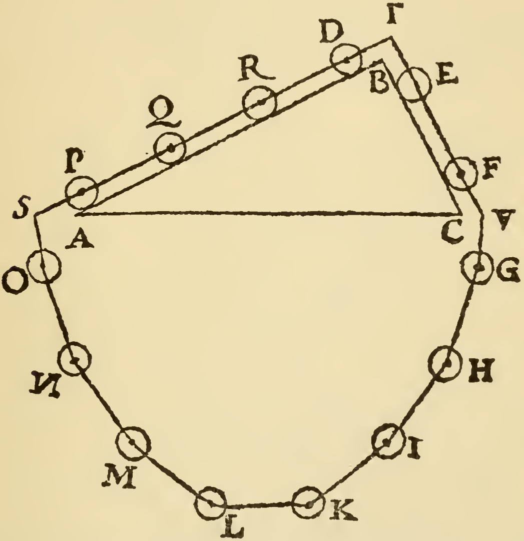

FIG. 4. STEVIN'S DEMONSTRATION OF THE LAW OF THE INCLINED PLANE

tain a weight which is proportional to the length of the plane. Another statement of the same result would be as follows: *along inclined planes of equal height, a given weight acts with a force inversely proportional to the length of the plane.*

From this theorem of Stevin's it is not difficult to pass to the parallelogram of forces, to which the first clear expression was given by Newton and Varignon in 1687.

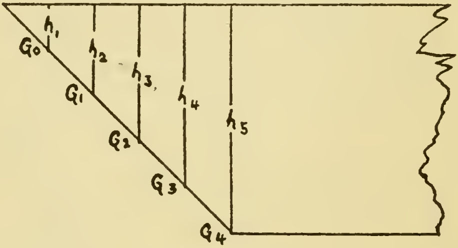

Fig. 5. Stevin's Method of Finding the Center of Hydrostatic Pressure

The upshot of the whole matter is to prove that these statical forces have the same properties as those of limited straight lines which mathematicians call vectors, *viz.*, *direction*, *sense*, and *magnitude*. But, the recognition that force is a vector quantity is all that is necessary to demonstrate the law of the parallelogram of forces. One may therefore consider this cogent experiment of Stevin's as a demonstration of the parallelogram law for forces.

Stevin's second achievement was the computation of the hydrostatic pressure on the side of a vessel containing a liquid. The method by which he did this is interesting because in it is contained the germ of the integral calculus, as will be seen from the following argument.

He first divides the side of the vessel up into a series of horizontal strips, g_1, g_2, etc.,—forming a series of rectangular areas; and then considers the pressure on the base of one of these, say g_1. This, he argues, is greater than would be produced by a prism of water of height h_1 and base g_1; it is also *less* than would be produced by a prism of height h_2 and base g_1.

By taking the sum of the pressures over the rectangles, Stevin thus obtains two sums one of which he knows is too large, the other too small; but as the rectangular strips are taken smaller and smaller these two sums approach one another and the common limit which their two sums approach he recognizes as the true value.

A more important contribution to the dynamics of floating bodies is the following. Archimedes long ago discovered two fundamental laws of hydrostatics, viz.,

(a) *Any body totally immersed in a liquid loses weight by an amount equal to the weight of the displaced liquid.*

(b) *Any body which floats displaces liquid to an amount equal to the weight of the floating body.*

To these Stevin added:

(c) *Any floating body assumes such a position that its center of gravity lies in the same vertical line with the center of gravity of the displaced fluid.*[9] This latter point is now called the "center of buoyancy."

(d) *In order that a body may float in equilibrium it is*

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[9] *Oeuvres Mathématiques*, p. 512.

necessary that the center of buoyancy lie at a higher level than the center of gravity of the floating body.[10]

In this last theorem, Stevin appears to have deceived himself; for the fact is that the center of buoyancy usually lies at a lower level than the center of gravity of the floating body. This error probably arose from a feeling after the *metacenter*, a third point introduced more than a century later by Pierre Bouguer (1698–1758).[11] The importance of the metacenter lies in the fact that its position relative to the center of gravity determines whether the equilibrium of the vessel is stable, neutral or unstable.

If the metacenter is above the center of gravity, the equilibrium is stable. If the metacenter coincides with the center of gravity, the equilibrium is neutral. If the metacenter is below the center of gravity, the equilibrium is unstable.

In general the man who first proposes an idea describes it with great directness and clarity. So here Bouguer defines the metacenter as that point beyond which the center of gravity of the vessel must not rise if the boat is to remain stable; a definition which many will consider distinctly simpler than the current one, namely, for any plane of tilt the metacenter is the center of curvature of the corresponding section of the surface of buoyancy. The exact words in which Bouguer defines the metacenter are the following:

> "Ainsi on voit combien il est important de connoître le point d'intersection *g*, qui en même tems qu'il sert de limite à la hauteur

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[10] *Oeuvres Mathématiques*, p. 513, Cor. I.

[11] *Traitê du Navire*, Paris, 1746.

qu'on peut donner au centre de gravité G, distingue le cas où le Navire conserve sa situation horisontale, de celui où il verseroit dans le Port même, sans pouvoir se soutenir un seul instant. Le point *g* qu'on peut, à juste titre, nommer *métacentre,* est le terme que la hauteur du centre de gravité G, ne doit pas passer, & ne doit pas même atteindre: car si le centre de gravité G étoit en *g*, le Navire n'affecteroit pas plus la situation horisontale que l'inclinée; les deux situations lui seroient également indifférentes: & il seroit par conséquent incapable de se relever, lorsque quelque cause étrangère l'auroit fait pancher."[12]

Stevin was also the earliest to introduce the decimal system in an effective manner. The late Professor Moritz Cantor, the historian of mathematics, estimates this part of Stevin's work as follows:

> "Decimal fractions had been employed for the extraction of square roots some five centuries before his time, but nobody before Stevin established their daily use; and so well aware was he of the importance of his innovation that he declared the introduction of decimal coinage, measures, and weights to be only a question of time."[13]

Stevin was also largely responsible for the introduction of double entry book-keeping and impersonal accounts in governmental business.

Along with Galileo, Stevin must be credited with the discovery of the principle of Virtual Work which was given its final form in a letter of John Bernouilli to Varignon under date of 26 Jan'y, 1717. Stevin states it as follows:

> *Ut spatium agentis ad spatium patientis sic potentia patientis ad potentiam agentis.* * * * The space through which any agent exerts a force is to the space through which it moves an object as the force exerted on the object is to the force exerted by the agent.

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[12] *Traité du Navire,* pp. 256–257.

[13] *Encyclopaedia Britannica,* "Stevinus."

His collected works were published at Leyden in 1605 under the title of *Mathematical Recollections* (*Hypomnemata Mathematica*). Twenty-nine years later these were translated into French by Albert Girard as the *Mathematical Works* (*Les Oeuvres Mathêmatiques*) *of Simon Stevin*, Leyden, 1634. At the time of his death, his fame rested largely upon his contributions to the science of fortification; and it will be recalled that he is constantly quoted in this connection by Uncle Tobey in Sterne's *Tristram Shandy*.

N. Copernicus, 1473–1543

Modern dynamics is so largely the child of astronomy that no sketch of medieval mechanics can fail to mention the great step made by Nicolaus Copernicus who was a student at the University of Cracow during Columbus' first voyage to America. In his *De Revolutionibus* (1543) —the first great work on astronomy since the *Almagest* of Ptolemy—he explains the main fact of relative motion, namely, that a rotation of the earth on its own axis would make everything outside appear to revolve in an opposite sense. Turning in another direction, Copernicus argues that if the earth has any motion other than that of rotation on its axis then this motion must be exhibited in celestial phenomena; and accordingly the annual motion of the earth about the sun is exhibited in the stations and retrograde motions of the planets. His conclusion, from a long line of evidence of which the above is a type, is that the sun is the true center of the world, and that the planets move about it in a series of concentric circles.

Copernicus stands in sharp contrast to most of his contemporaries as being no mere scholiast. He is not editing the views of other men. He is indeed an inspiring example of a clear and independent thinker. His attitude of mind and the spirit of the times are each reflected in the two following paragraphs from the preface of his monumental book.

Dedication of the "Revolutions of the Heavenly Bodies,"

by Nicolaus Copernicus (1543)

to Pope Paul III

"I can easily conceive, most Holy Father, that as soon as some people learn that in this book which I have written concerning the revolutions of the heavenly bodies, I ascribe certain motions to the Earth, they will cry out at once that I and my theory should be rejected. For I am not so much in love with my conclusions as not to weigh what others will think about them, and although I know that the meditations of a philosopher are far removed from the judgment of the laity, because his endeavor is to seek out the truth in all things, so far as this is permitted by God to the human reason, I still believe that one must avoid theories altogether foreign to orthodoxy. Accordingly, when I considered in my own mind how absurd a performance it must seem to those who know that the judgment of many centuries has approved the view that the Earth remains fixed as center in the midst of the heavens, if I should, on the contrary, assert that the Earth moves; I was for a long time at a loss to know whether I should publish the commentaries which I have written in proof of its motion, or whether it were not better to follow the example of the Pythagoreans and of some others, who were accustomed to transmit the secrets of Philosophy not in writing but orally, and only to their relatives and friends, as the letter from Lysis to Hipparchus bears witness. They did this, it seems to me, not as some think, because of a certain selfish reluctance to give their views to the world, but in order that the noble truths, worked out by the careful study of great men, should not be despised by those who are vexed at the idea of taking great pains with any forms of literature except such as would be profitable, or by those who, if they are driven to the study of Philosophy for its own sake by the admonitions and the example of others, nervertheless, on account of their stupidity, hold a place among philosophers similar to that of drones among bees. Therefore, when I considered this carefully, the contempt which I had to fear because of the novelty and apparent absurdity of my view, nearly induced me to abandon utterly the work I had begun.

"My friends, however, in spite of long delay and even resistance on my part, withheld me from this decision.

* * * * *

"Nor do I doubt that ingenious and learned mathematicians will sustain me, if they are willing to recognize and weigh, not superficially, but with that thoroughness which Philosophy demands above all things, those matters which have been adduced by me in this work to demonstrate these theories. In order, however, that both the learned and the unlearned equally may see that I do not avoid anyone's judgment, I have preferred to dedicate these lucubrations of mine to Your Holiness rather than to any other, because, even in this remote corner of the world where I live, you are considered to be the most eminent man in dignity of rank and in love of all learning and even of mathematics, so that by your authority and judgment you can easily suppress the bites of slanderers, albeit the proverb hath it that there is no remedy for the bite of sycophant."[14]

Between Copernicus, who proposed a natural and simple view of the solar system and Kepler who unraveled the motion of the planets, there was need of an accurate observer who should definitely locate the positions of the various heavenly bodies at particular times. This man appeared in the person of a most remarkable Dane.

[14] From *Harvard Classics*, vol. 39, pp. 55–59.

Tycho Brahe, 1546–1601

The first observer of any consequence since the time of Hipparchus, unless we include Ulugh Beg, was Tycho Brahe. Born at the southern end of Sweden, in a little town called Knudstrup, Tycho was nevertheless a Dane; for that part of Sweden then (1546) belonged to Denmark. During his entire eudcation (which was obtained at the universities of Copenhagen, Leipsic, and Rostock) he devoted himself to astronomy on the side; but he was especially stimulated by the famous new star which appeared in Cassiopeia. It was in his well known observatory at Uraniborg that he collected a great mass of observations on comets, on the moon, on the planets, and on the positions of 777 fixed stars, all of which proved to be of the utmost value to his brilliant pupil and successor, John Kepler. The telescope was not yet available; accordingly he used a seven-foot quadrant. Tycho Brahe also substituted the equator for the zodiac as an axis of reference, thus introducing the modern coördinates, right ascension and declination, instead of longitude and latitude. In June, 1599, Tycho moved to Prague and here he died on October 24, 1601.

In Tycho Brahe's picture of the heavens he placed the earth at the center of his cosmos; and yet he kept the sun at the center of the planetary system, a curious mixture of Ptolemaic and Copernican ideas.

Within ten years after the death of Tycho Brahe, the telescope had been invented but this did not diminish the value of his observations to his eminent successor, the last of the three outstanding astronomers of medieval times.

John Kepler, 1571–1630

In fact, Kepler used these observations in such a superb manner that one feels scarcely any break in the continuity of the work when Tycho Brahe steps off the stage and Kepler comes on. It was down in the southwest corner of Germany in a town called Weil that Kepler was born in the year 1571 when Shakespeare was a boy of seven. Enfeebled by premature birth, afflicted by smallpox at the tender age of four, unhappily married, he was never without trouble. At the University of Tübingen, he developed rapidly and made lifelong friends. He met Tycho at Prague in August, 1600. Fourteen months after this meeting, Tycho died and Kepler became not only his scientific legatee but also his successor as the court mathematician of Upper Austria.

What Kepler accomplished in optics we shall consider shortly under that heading; what he did in physical astronomy is summarized in what is now universally known as "Kepler's Laws." In the order in which he announced them they are as follows:

(i) The orbit of each planet is an ellipse with the sun in one of its foci.

(ii) The radius vector of each planet describes equal areas in equal times.

(iii) The squares of the periods of the planets are proportional to the cubes of their mean distances from the sun.

The formulation of this third principle is something for which Kepler had been searching during all the seventeen years between 1601 and 1618.

To appreciate the significance of these discoveries, one must look both backward and forward; he must observe that they profoundly modify the system of Copernicus with its circular orbits and he must also remember, that from the first of these laws Newton proved the inverse-square law of gravitation and from the second he showed that the force which retains any planet in its orbit is a radial one directed toward the sun. Kepler's own ideas of mechanics seem to have been quite as vague as those of his contemporaries. Galileo had not yet (1610) announced the law of inertia and Kepler naturally supposed the motion of a planet would soon cease unless sustained by some force at its back—some *vis a tergo*—pushing it along, in a tangential direction.

The earliest astronomer of note to fully and unreservedly accept these radical results of Kepler was the brilliant young sizar of Emmanuel College, Cambridge, Jeremiah Horrocks (1619–1641) who predicted the first observed transit of Venus (1639), and who died at the remarkably early age of twenty-two.

During the wonderful half century which intervened between the death of Kepler in 1630 and the publication of Newton's *Principia* in 1687, many attempts were made to substitute other rules for the behavior of the solar system; but none of these furnished any improvement; nor was any one more successful than Kepler in his vain search for the cause of planetary motion. What Kepler accomplished under the most distressing circumstances of mind, body, and estate must ever remain one of the out standing marvels of history. He was sustained by the uncompromising friendship of a few men. Carol Wight in his poem, *Kepler's Death*, makes him say:

"Still Tuscany's Arch-Duke,—I must recall
One pleasing memory,—sent to me a chain
Of purest gold,—fit emblem for the man,
Who chained the planet Mars by lasting law;
Yet sweeter comes this honor inspired by him.
Great Galileo, he whose friendship still
Sweetened my life, now solaces my death.
Thee may thy fellow-countrymen accord
The love and honor mine deny to me!
O Tycho Brahe, my deep debt to thee,
For food when famished, homeless for a home,
While sickness and want afflicted me and mine,—
My promise at thy death-bed pledged,—at last
Is paid in full, God only knows with what
Dire deprivation."[15]

MEDIEVAL OPTICS

It is not a little remarkable that during the very period in which such powerful and valuable inventions as gunpowder (1250), printing (1450), the mariner's compass (1269), linen paper (1150) and the art of navigation were being developed, that a pure science such as optics made little progress; but this is only another illustration of the fact that commerce and travel and the work of every day life have nearly always furnished the foundation upon which pure science has been built. An analogue is found perhaps in the fact that in the long run economics dominates political science and diplomacy.

It is fairly clear that spectacles came into use about the end of the thirteenth century; but whether they were invented by Allessandro de Spina or by Salvino degli

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[15] *The Johns Hopkins Alumni Magazine*, 9, p. 43.

Armati of Florence, or by some third party is not so evident. It is highly probable, however, that the invention was made in Italy; and that nothing else of importance in optics was done until two lenses were combined to produce an astronomical telescope some three hundred years later.

Much might be said about Roger Bacon's study of the focal properties of the concave mirror, about Vitello's treatise on optics, about Telesius (1508–1588), the founder of the *Academia Consentina*, the main object of which appears to have been the discovery of Aristotle's errors in optics and other branches of science; or about John Peckham, an English Franciscan monk, archbishop of Canterbury and contemporary of Roger Bacon. But I have been unable to find any contribution of permanent value to the science of optics by anyone of these. The *camera obscura*, an instrument of which the periscope and the human eye are well known modern examples, is an invention which we apparently owe to the Italian, Daniello Barbaro. Major-General James Waterhouse who has made a careful study of this subject finds that Barbaro used a convex lens for projecting, in a darkened room, the image of an outside object some twenty-one years before the mention of it by J. B. Porta (1538–1615) to whom the device has usually been assigned. The work in which Barbaro gives this description is his *La Practica della perspettiva*, page 192, 1568.

The principal interest which here attaches to the camera obscura lies in the fact that it is somewhat of a connecting link between the single lens and the telescope. It is, in fact, the next step after the solution of the ancient question put by Aristotle[16] as to why a square hole in the side of a darkened room gives a round image of the sun—a solution first given by F. Maurolycus (1494–1577).[17]

It was about this time that the superb phenomenon of the rainbow was first seriously studied. Aristotle had long ago erroneously explained it as a case of reflection; but the Jesuit priest, M. A. de Dominis (1566–1624) of Spalatro in Dalmatia, showed by experiment with a glass globe filled with water that it is really produced by refraction as well as by reflection. The rays of light from a source placed in front of the globe and refracted by the globe were found to produce roughly the effect of rain drops in sunshine. Maurolycus also broke a lance on this difficult problem as did Theodoric of Saxony before him. The complete explanation belongs to modern times and is as usual the cumulative achievement of a series of brilliant minds; in this case, of Descartes, Halley, Newton, Young and Airy. At the present time it is perfectly evident, that no very great permanent progress in optics could be made until the accurate law of refraction had been discovered; and this law was not found until the beginning of the modern period.

In the meantime, it is rather surprising to see what a brilliant mind, such as that of Kepler, was able to accomplish without either the fundamental law of refraction, $\mu \sin \theta =$ *invariant*, or the fundamental law connecting conjugate focal lengths, $\frac{1}{p} + \frac{1}{q} = \frac{1}{f}\cdot$ Kepler's first work on optics—*A Supplement to Vitello*, Frankfort, 1604—a quarto volume of 424 pages, written in Latin, of course, was by no means so important as his much smaller volume, *Dioptrics*, published at Augsburg in 1611. Only one year before this, Galileo's *Sidereal Messenger* had made its appearance. Here were detailed some of his most important discoveries with the newly invented telescope, such as the four satellites of Jupiter and the phases of Venus. In his *Dioptrics*, Kepler sets out to construct the theory of the telescope, basing it upon a few fundamental definitions and theorems of which the fundamental one (VII) is the following: *For angles of incidence less than 30 degrees, the deviation of the refracted ray is proportional to the angle of incidence;* or, as we should now say, $\frac{\delta}{i} = \frac{i - r}{i} = constant$, where i is the angle of incidence, r the angle of refraction, and δ that of deviation.

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[16] *Problems*, section XV, Chapter 10.

[17] *Photismi de lumine et umbra*, Venice, 1575.

Kepler's next axiom (VIII) is that the value of this *constant* for ordinary glass is 1/3; which in modern terminology amounts almost to assuming the value 1.5 for the refractive index; since then $\frac{i - r}{i} = \frac{n - 1}{n} = 1/3$ approximately. Upon this basis, he first proceeds to compute the position of the principal focus for three different cases.

(i) For light passing from air to glass, through a single refracting surface, the principal focus is *three* radii behind the surface.

(ii) For light passing from glass to air, through a single refracting surface, the principal focus lies *two* radii behind the surface.

(iii) For a double convex lens, the principal focus lies *one* radius behind the lens.

How nearly Kepler was correct will be seen by applying the following ordinary formulae for paraxial rays to glass whose refractive index is 1.50 instead of the customary 1.52.

(i) For a single refracting surface, radius r, index μ, light passing from air to glass, $f = \dfrac{\mu r}{\mu - 1} = 3r$.

(ii) For light passing from glass to air, $f = \dfrac{r}{\mu - 1} = 2r$

(iii) For a double convex lens, $f = \dfrac{1}{\mu - 1}\,\dfrac{r_1\,r_2}{r_2 - r_1}$ $= r$, when $r_1 = -r_2 = r$.

In addition to this, Kepler arrived at the fact (Theorem XLI) that when the object-distance is twice the focal length, then the image-distance is also twice the focal length, thus showing that he was very near the exact law of conjugate foci. In Problem 86 of his *Dioptrics*, one finds the description of the modern astronomical telescope, using the double convex eyepiece; but it does *not* appear that Kepler ever actually constructed such an instrument. C. Scheiner (1575–1650) a few years later made and used one in his observations of the sun, (*Rosa Ursina*, 1630) in the manner indicated by Kepler in Problem 88. In Problem 105, Kepler describes the combination of a double convex objective, backed by a double concave lens, which we now call a *telephoto* lens.

To Kepler we owe also the discovery of total reflection. This he ran across by following to its logical conclusion the law of the reversal of the ray—what the French call *le principe du retour des rayons*—inquiring what would happen when the angle of incidence, in glass say, lay between the critical angle and 90 degrees. He found such a ray by experiment to be totally reflected, a discovery which led to the beautifully precise and convenient refractometer of Abbe, now in common use all over the world.

RÉSUMÉ

Considered as a whole, the striking feature of medieval optics is the creation and development of dioptrics. Nothing came down from the ancients upon which modern optics could build except the single law of reflection. It is now clearly evident that further advances had to wait upon the laws of refraction and diffraction which belong to the modern period. Nevertheless Kepler, within the brief eighty pages of his *Dioptrics*, showed us that, with a mere approximation to the law of refraction, he could explain many optical instruments, including the human eye, and could indeed make more progress than all his predecessors put together.

In the domain of electricity no new phenomena were discovered during the middle ages. The whole science was up to the time of Gilbert (1540–1603) limited to the one fact described by Thales, namely, amber when rubbed will attract light bodies. The case of magnetism is somewhat different; for although the natural magnet was well known to the ancients, it would appear that the artificial magnet used as a mariner's compass came into vogue about the year 1190. The first pivoted compass was described by Petrus Peregrinus in 1269. It is not certainly known who first observed the deviation of the compass; but it is well established that Columbus during his first voyage to America determined a line of no magnetic variation—the line along which the needle points to the true north. In 1544 Georg Hartmann of Nuremberg first found that a pivoted needle as soon as it is magnetized dips down at the north end. Nothing else of importance was accomplished before the time of William Gilbert whose work we assume to mark the beginning of the modern period. Mottelay[18] gives the medieval history of magnetism with great completeness.

In the science of heat, no quantitative work was possible before the invention of the thermometer, another instrument which belongs to the first years of the modern period. Some progress is indicated, however, in the apparatus invented by G. B. Porta (1538–1615) of Naples in 1601 for driving the water out of a closed chamber by use of steam generated in a separate vessel. This device of Porta's is the connecting link between the hot air chamber employed by Hero (130 B.C.) for opening the doors in front of a shrine and the earliest successful steam engine, the one patented by Savery in 1698. Porta will be remembered not only for his work in optics and heat, but also for his founding of the Accademia dei Oziosi at Naples, in 1560, in which the condition of membership was "to have made some new discovery in natural science."

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[18] *Bibliographical History of Electricity and Magnetism*, Griffin, London, 1922.

CHAPTER V

THE BIRTH OF MODERN PHYSICS—THE GREAT TRIO

> "The dead but sceptered sovereigns who still rule
> Our spirits from their urns."
> —BYRON: *Manfred*, iii, 4.

"Modern Science," said Sir Arthur Schuster in his presidential address before the British Association for the Advancement of Science in 1916, "began not at the date of this or that discovery but on the day that Galileo decided to publish his *Dialogues* (1632) in the language of his nation." Another profound student of the history of physical science, the French chemist Duhem, insists that:

> "If one wishes to draw a line of separation between the realm of ancient and modern science, it must be drawn at the instant when Jean Buridan conceived his theory of momentum, when he ceased to think of the stars as kept in motion by certain divine beings, and proclaimed that motions, celestial and terrestial, are each controlled by the same mechanical laws."[1]

The exact date of Buridan's birth is unknown; but it is not far from the year 1300. Duhem's line of separation between ancient and modern science is thus some three centuries earlier than Schuster's; and this in face of the fact that both are considering the same field, namely, dynamics. The difference of opinion here expressed is largely one of interpretation and emphasis.

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[1] *Études sur Leonard de Vinci*, vol. 3, p. ix.

The line of demarcation might have been drawn at many other places between these two extremes. Science does not come to us as a finished product, but grows just as truly as plants grow. It developes just as nations develop, and the laws of science have evolved just as truly as the laws of nations have evolved. Efforts to discover the origin of modern civil law have pushed the date back to at least the code of Hammurabi which is something like 2500 B.C. compared with which the American Constitution, the Magna Charta, and the great body of Roman Law are all recent documents. Precisely the same thing has been happening in the domain of physical science. There are no sharp lines anywhere; not even at the beginning of the seventeenth century which the author has, arbitrarily and for present purposes only, selected to mark the beginning of modern science. The learning of the ancients is like the game of golf; the greater the care with which one examines it the more he finds in it to approve and admire; and either may be pursued to the point where one is filled with despair.

We begin with the development of kinetics which is largely the achievement of three different minds, Galileo, Huygens and Newton, representing three different nations.

GALILEO, 1564–1642—HIS LIFE AND WORK

The first of this trio was born at Pisa in the same year with Shakespeare, at a time when Florence was the center of art, Rome the center of Catholicism, and Padua the center of science; when, in fact, Italy was the land of "sweetness and light." The father was descended from a brilliant Florentine family, now come upon hard times. Their residence in Pisa seems to have been brief; for at the age of twelve the lad was taken to Florence and placed in school at Valambrosa, where he remained until, at the age of seventeen, he entered the then recently established University of Pisa. After four years of student life, resulting in no degree, but resulting also in no atrophy of intellectual power, he returned to Florence, where he spent another quadrennium in finding himself; not four years of idleness, but four years of earnest endeavor, devoted to the study of Euclid and Archimedes, to the invention of a direct reading hydrostatic balance, and to the solution of certain center-of-gravity problems. The end of this period brought him to the age of twenty-five and to the chair of mathematics in the University of Pisa. The records show that his munificent salary of $65 a year was diminished by 10 per cent on account of absences. However, the purchasing power of the pittance that remained, was very welcome to this generous-hearted young man, who had already obligated himself for the full amount of his sister's dowry. He was now a colleague of the men in whose classes a few years before he had asked questions so embarrassing as to lead them to dub him the "wrangler." That detachment from current opinion and that olympic independence which were to characterize the next fifty years of his life at once began to show themselves. For it was during the first year of his professorship at Pisa that he circulated his paper "On the Motion of Heavy Bodies" in which for the first time are clearly set forth those notions of velocity and acceleration which we to-day consider modern and valid.

Oddly enough the paper in which these definitions are given was not published until the two hundredth anniversary of his death.

The main lines of the new mechanics which are highly original and fundamental, were laid down at Pisa while Galileo was still a young man, between twenty and thirty. The opinion of posterity will, probably, assign more permanent value to these new dynamical conceptions than to all the rest of his work put together—not to mention the fact that Galileo himself never claimed to be the inventor of the telesceope.

It is a curious fact that in the twenty quarto volumes which contain the work of Galileo there are only two scant references to the experiment for which he is perhaps most celebrated, namely, his dropping of the different bodies from the leaning tower at Pisa, in order to prove that light and heavy bodies fall with the same speed.[2]

However, men of permanent eminence are nearly always surrounded by legend; so, in this case, tradition has supplied all and probably more than history lacks; later writers have not hesitated to give the weight of the shot which he used, and to describe the bystanders—possibly on the principle of the gentleman who had such high regard for the truth that he always liked to ornament it just a trifle.

The leaning tower experiments spoke so effectively against the views professed by his colleagues that the entire faculty, with a single exception, was turned against him, and his resignation was handed in before the end of the three-year engagement for which he had contracted. In the meantime, friends had secured for him the chair of mathematics at Padua, a focus of learning which was then attracting strong men from England, Holland, and France. This move, in 1592, brought him into a congenial atmosphere; for his associates were lofty minded men, scholars of the first rank, including the surgeon, Fabricio, known as "the Columbus of the human body," the successor of Fallopius and the teacher of William Harvey. Among his friends was the real Sagredo, a Venetian gentleman who appears, as a clever interlocutor, in all his *Dialogues.* Among his students, Galileo had men of the type of Cavalieri and Castelli and, with one exception, the entire group who later (1657) formed the Florentine Academy. His lectures covered subjects as diverse as geometry, mechanics, heat, astronomy and fortifications; but through them all, he satisfied completely the criterion of the late President Gilman for the American professoriate—"a student who can also teach."

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[2] Cajori, *Science*, October 29, 1920.

Resulting from the studies of Galileo at Padua, we have the invention of the air thermometer and a series of important astronomical discoveries, including the phases of Venus, four satellites of Jupiter, the "triple nature of Saturn," and the rotation of the Sun. In 1610, Galileo accepted an invitation to Florence as "Philosopher and First Mathematician to the Grand Duke of Tuscany," little dreaming with what consequences this crossing of the Apennines from the freedom of the Venetian Republic to the dominion of the Pope was fraught. Among the churchmen of those days were to be found the best trained minds in Europe—men who also possessed rare ability in translating problems of physics into problems of theology—men who are not without representation in recent times; for Mr. Huxley and Mr. Darwin found some of the pillars of the church "alarmed lest man's nature be debased by the increase of his wisdom."[3] It was a time when heresy was practically equivalent to treason. In 1615, the Holy Congregation declared that all books of Copernican doctrine were condemned and prohibited. In 1630, when Galileo had completed the manuscript in which were set forth the well established facts of observation concerning the system of the stars, he made his fifth journey to Rome, this time seeking an *imprimatur* for his new book. The Holy Office granted permission under two conditions: (i) that the author should state in the preface that the treatment was "from a purely hypothetical standpoint," and (ii) that the book should conclude with the following argument which the Pope had advanced to Galileo some six years earlier, namely, God is all-powerful; to Him all things are, therefore, possible; consequently no physical phenomena can be adduced as *necessary* proof that the earth rotates on its axis and revolves about the sun.

These two unworthy and humiliating conditions were assented to by Galileo. To what extent this man of sixty-six years was driven by ill health, to what extent he was urged by the fact that a good portion of his life's work lay in this manuscript, it is impossible ever to know.

Two years later, February 22, 1632, just one hundred years before the appearance of George Washington and only four years before the foundation of Harvard College, this imperishable volume issued from the press at Florence. The complete edition was immediately exhausted. The three interlocutors were Sagredo, his old Venetian friend—a keen wit; Salviati, his most intimate friend at Florence as well as his own spokesman, and Simplicio, a much earlier commentator on Aristotle, who stands for the peripatetic philosophy and the Ptolemaic system. However, it was apparently an easy matter to convince the Pope that he himself had been satirized under the name of Simplicio. The result of this was that Galileo's case was turned over to the Inquisition and he himself was summoned to Rome in midwinter.

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[3] *Lay Sermons*, p. 143.

This trip, forced upon him without consideration of age or health or preeminence, was his sixth, his last and most memorable visit to that city. Again he was the guest of the Tuscan ambassador and again the recipient of every courtesy except the one most longed for, namely, intellecutal sympathy and intellectual freedom.

What took place at the trial of Galileo, including the indictment, the sentence and the abjuration is so well known in general and so much disputed in detail that there is no need to enter upon generalities. Each reader will form his own opinion.[4]

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[4] A modern counterpart of Galileo's abjuration and his celebrated remark *Eppur si muove* is perhaps that of the Belgian cripple who limped about Brussels during the World War. One day when he was heard to remark "We gave those Germans a rare hiding before they got to Brussels," he was informed by a German officer that he would be shot unless he became German. The cripple accepted the inevitable and was immediately sworn in. The officer took him by

It ought to be remarked, however, that Urban VIII, the Pope under whom these things happened, accepted the papacy largely on account of the temporal power connected with it, that he was a man of military ambitions, one of the Barberini family, the man who fortified the Castel Sant' Angelo with cannon made from the bronze of the Pantheon, which led the Romans to satirize him with the epigram "Quod non facerunt barbari, facerunt Barberini."

Shortly after the close of this sorrowful drama of 1633, the aged scholar was allowed to find shelter under the hospitable roof of one of his former students, Piccolomini, now an archbishop at Siena. Here this indomitable spirit—this "unconquerable mind of man"—resumed the study of that subject which had commanded his earliest thought and the most of his energy—mechanics. In the brief period of five months of enforced leisure at Siena, he practically completed his great treatise on dynamics in which he exhibited that same power of detachment from the views of others that had characterized his earlier years. The finished product issued from the press of the Elzevirs in 1638, under the title of *Discourses on Two New Sciences.* Publication in Italy was, of course, quite out of the question, everything from the pen of Galileo having been prohibited, *nullo excepto.*

As has been indicated earlier in this discussion it is doubtful whether any book can rightfully be called "the first work on modern physics;" but, if this title is to be

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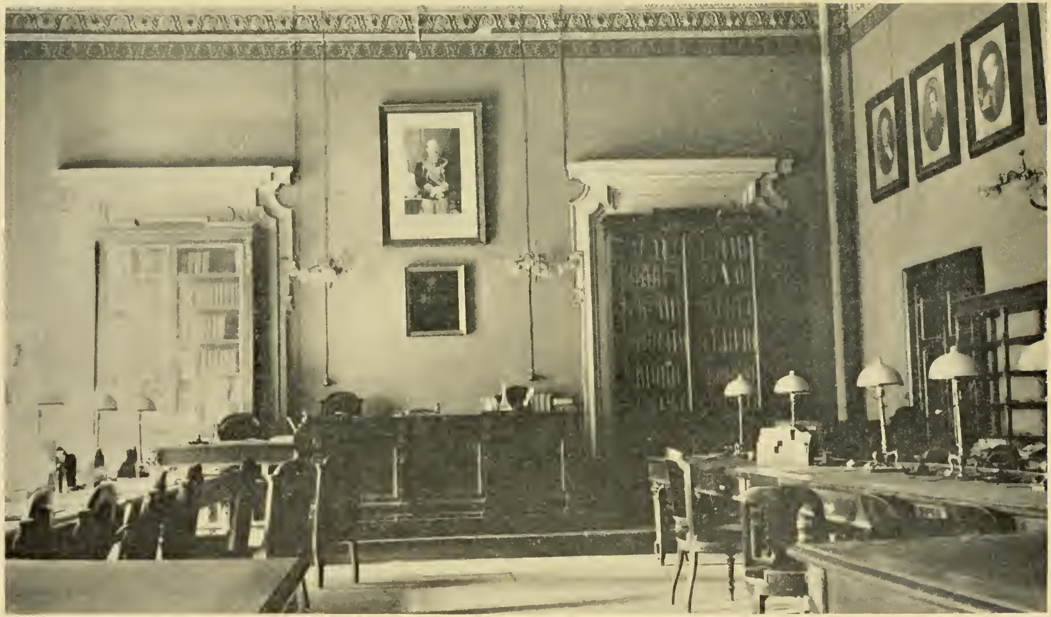
the hand saying "You are German now!" The cripple left the room muttering "Those Belgians gave us a rare hiding before we got to Brussels!"



The Room in Which Galileo Was Forced to Recant in 1633, then Part of a Dominican Convent; now Used by the Ministry of Education

allowed, it certainly belongs to the *Two New Sciences;* the pages of which "contain," says Galileo, "results which I consider the most important of all my studies." The manuscript was quietly handed to Louis Elzevir during a visit to Galileo at Arcetri in 1636 and two years later appeared from the Elzevir press at Leyden.

The facts which warrant anyone in ranking it as the first book on modern physics are the following:

(i) Here for the first time one finds carefully planned and accurately executed experiments used as a means for acquiring new facts. This impersonal verification of phenomena added a new method to science. No greater mistake could be made than to suppose that Galileo was the first man to differ with Aristotle; the Academy of Cosenza (Academia Consentina), having opposition to the peripatetic philosophy as its avowed purpose, was established by Telesius and his friends at Naples about the time when Galileo was born; but he *was* the first man to offer *experimental evidence* against the conclusions of Aristotle; and in so doing he established what we now call the experimental method.

Only two methods of investigation were known to the ancients, the philosophical and the mathematical; to these Galileo added a third, the experimental. The philosophical method consisted in assuming certain general principles and trying to find in them an *a priori* explanation of the universe. Briefly described, the attempt was to stare nature out of countenance. Failure was inevitable, not for want of intellectual acumen, but because, as every one knows, it sometimes requires a lifetime of effort to explain a single detail. Witness almost any chapter in Darwin's *Origin of Species.* Details must be mastered before one can pass to general principles.

The mathematical method consisted only in applying geometry to certain well-known areas, volumes and angles, especially to those angles observed in the sky, but always with the idea of describing the known rather than of discovering the unknown; the mathematicians do not appear to have put any deliberate questions to nature.

In all of Galileo's thinking nothing is exempt from experiment. Even astronomy in his hands ceases to be a purely observational science; for when he wishes to discover whether the bright portions of the moon's surface are rough or smooth, he sets up two surfaces, one rough and one smooth; then illuminates them with Italian sunlight. Desiring to learn at what rate falling bodies gain speed, he devises a time-measuring machine, invents a method of "diluting gravity" and actually measures the rate at which speed is gained. His discussions begin and end with experiment—a method so familiar to us that we forget how recent and powerful it is.

His two great dialogues—one dealing with astronomy, the other with mechanics—abound in experiments—most of them apt and clever. Leonardo da Vinci advocates experiment; Galileo uses experiment.

(ii) The second great achievement of Galileo was his seizure upon momentum as the fundamental quantity in the science of mechanics, and his demonstration that velocity is a factor in momentum. Galileo was by no means the first to study and discuss kinematical problems.

Benedetti (1530–1590), one of the many distinguished alumni of the University of Padua, had not only expressed dissatisfaction with the artificial distinction between "violent" and "natural" motions, but had gone farther and had paved the way for mechanics and the differential calculus by recognizing the fact of continuous variation in motion: Benedetti[5] had in particular studied oscillatory motion and had shown that such a motion is continuous even when the vibrating particle is at rest at the end of its path. He had, in fact, introduced the modern idea of continuous variation. But none of the predecessors of Galileo had, so far as I have been able to discover, pushed their study of moving bodies beyond the mere consideration of change of position. None of them had recognized the inertia of the moving body as a fundamental—perhaps the fundamental—fact of mechanics. Princes and paupers, for ages, had stumped their toes against bricks and stones: they were doubtless quite as familiar as we with the mere fact of inertia. But to Galileo it was a cardinal fact, because he was the first to see that the future history of a body depends upon its possession of inertia. To him the importance of a motion is, in general, measured by the inertia involved, or as was then said—the weight involved. Hence he assigned to the product of the weight and velocity of a body the name "momentum," a Latin word which sometimes denotes motion and at other times importance, but which is here used to denote both motion and importance; as a synonym he sometimes uses the word *impetus*, thus emphasizing the impetuosity of motion.

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[5] Lasswitz, *Atomistik*, 2, pp. 14–23, gives a good description of Benedetti's work.

But Galileo never got beyond the point where he measured inertia by weight, as indeed engineers still do—all, at least, except electric engineers.

Those who wish to see just how clearly Galileo conceived that the future behavior of a body is connected with its inertia should read those propositions in his *Mechanics*[6] in which he calculates the path of a projectile by assuming that the horizontal speed of a shot, after it has left the muzzle of a gun, continues to be uniform. His repeated use of this principle makes it perfectly clear that he discovered what we now call—and perhaps properly call—Newton's first law of motion. Galileo failed to generalize it by extending it to all bodies, whether subject to the earth's gravitation or not. This Newton did because he had acquired the new concept of mass—that constant property which never deserts a body in any position or condition.

(iii) The next great step which Galileo made, was the discovery of the constant factor in the motion of falling bodies. One of his earliest experiments, performed while still a young man at the University of Pisa, was to allow a bronze ball to roll down a carefully prepared inclined plane, an experiment from which he cleverly inferred that while the position and speed of the ball were changing, the time-rate at which it gained momentum remained constant. The experiment is completed by showing how one can compute the momentum (or speed) of a body after it has been falling for any given time or through any given distance. In all these computations, the unit of momentum employed is that which a body acquires in falling freely through an arbitrarily selected unit of distance. The following simple description of the motion of freely falling bodies with which every student of general physics is familiar was first given by Galileo.

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[6] Galileo, *Dialogues on Motion*, Fourth Day, Problem I, et seq.

$$\begin{cases} V = V_0 + gt \\ S = S_0 + V_0t + \frac{1}{2}gt^2 \\ V^2 = V_0^2 + 2gS \end{cases}$$

As illustrating how tenaciously he clings to the idea of momentum, witness the following clear, exact and thoroughly modern definition dating from the year 1604:

> "I call a motion uniformly accelerated when starting from rest its momentum, or degree of speed, increases directly as the time, measured from the beginning of the motion."[7]

Observe that we have here, without any mention of the word, precisely the dynamical idea which we to-day use under the name of a "*constant force.*" There is, indeed, no necessity for the name; for Galileo attempts nothing more than to discover how the momentum of a body changes, owing to the presence of another body such as the earth in the neighborhood (action at a distance) or owing to contact with an elastic body such as the hot gases of exploding gunpowder in the barrel of a gun (action through a medium). Later generations had not yet beclouded the idea of force with "tendencies to motion;" they had not yet identified it with that vastly more complex "muscular sensation;" they had not yet made it over in the form of a "man;" they had not yet named it an "agent;" they had not yet identified it with a state of stress or strain which one elastic body exhibits when held permanently at rest by another elastic body; still less had there been any attempt to convince people—principally high-school lads and college students—that all these various things are one and the same, since, forsooth, at various times we call them by one name, "force." Some of Galileo's most worthy successors, such as Clifford,[8] Poincaré[9] and Hertz, have pointed out our inconsistent definitions of force, and have advocated in the most outspoken manner a return to the simple methods of this Italian academician.

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[7] Le Opere di Galileo Galilei., Nat. Ed., 2, p. 166.

The best known of all his experiments is, of course, that in which he proves that the time of fall is independent of weight, an experiment which completes to a first approximation the laws of falling bodies practically as we have them today. He accomplishes a second approximation by eliminating the buoyant force of the medium. He is prevented from making a third approximation only because he meets the barrier of viscosity, a barrier which still renders impossible the solution of any but a few simple cases in fluid motion.

The one remaining fundamental phenomenon of falling bodies is that the acceleration of gravity is independent of the substance of which the falling body is composed. This Galileo[10] proved by swinging, side by side, two pendulums, having bobs of lead and cork, respectively. When the suspension fibers had equal lengths and the pendulums swung through equal amplitudes, they had equal velocities at each point of their path. It is difficult to find, in Newton's hollow pendulum experiment, much more than a second approximation in which he eliminates the air resistance from this experiment of Galileo.

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[8] Clifford, *Nature*, 22, p. 122, 1880.

[9] Poincaré, *Lecture before the Wissenschaftliches Verein in Berlin.* p. 116, Teubner, 1912.

(iv) The fourth advance which we owe to Galileo is the observation that any momentum communicated to a body in one direction does not alter the momentum of the body in a direction at right angles. This independence of components of momenta, now known as Newton's second law of motion, was in the hands of Galileo no mere philosophical theorem, no vague guess, but a practical rule of action to be employed in mechanical operations. It is by compounding a uniform horizontal velocity with an accelerated vertical velocity that he proves, for the first time, that the path of a projectile must be a parabola. It was by means of this principle that he prepared a range-table for gunners. The fact is then that Galileo discovered and employed the first two of Newton's laws essentially as we use them today, and this Newton himself asserts in the *Principia*.

In conclusion, it may be said that mechanics is the one subject to which Galileo was consistently and persistently devoted; it was the subject of his earliest investigation when a young man at Pisa; the subject upon which he lectured when in his prime at Padua; the subject of his latest and most mature reflection at Arcetri. The thing for which he will never be forgotten is his introduction of the idea of force as a mere synonym for the time rate of variation of momentum—an idea which carries with it, immediately, the first and second of Newton's Laws of Motion.

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[10] *Two New Sciences*, p. 84, Macmillan, 1914.

It is possible, however, that his most important contributions lie outside the domain of physics. For his life still teaches that nothing is so because any man says it is so. His example still shows how experiment can rob a man of all arrogance of opinion, how familiarity with unsolved problems can give a man genuine humility and how, on the other hand, the possession of clear experimental evidence arms him with sure confidence.

CHRISTIAAN HUYGENS, 1629–1695

There are many links connecting the work of Stevin and Galileo with that of Newton and Lagrange; but the all important one is that furnished by Christiaan Huygens, the "Dutch Archimedes," who distinguished himself in three more or less distinct fields of science; mathematics, physics, and physical astronomy. It is here proposed to consider only the additions to the edifice of dynamics which he built upon the foundation of his predecessors. First, however, a word about his life.

Christiaan Huygens was the second son of an unusually brilliant father, Constantijn Huygens, poet and diplomatist, whom Edmund Gosse calls "the most brilliant figure in Dutch literary history.' The son was born at The Hague in 1629 and died there in his sixty-sixth year. Three years of university training at Leyden and Breda, much travel and a rare group of associates, added to his splendid ancestry and home training, gave him an education which left little to be desired. Most of his life was spent in Holland; but, for the fifteen years following 1666, he was the guest of Louis XIV and the then recently founded French Academy of Sciences. This was for him a happy period of great activity and it was only in anticipation of the revocation of the Edict of Nantes that he returned to his own country, where in private retirement and study he spent most of his remaining years. In 1663 he had been elected to membership in the Royal Society of London; and, like his fellow-members, Newton, Hooke, and Leibnitz, he remained a bachelor. *Les Oeuvres Complètes de Christiaan Huygens* have been in process of publication since 1888, by the aid of the Société Hollandaise des Sciences, in a series of worthy quarto volumes, of which the latest (vol. 15) appeared in 1925.

Invention of the pendulum clock

Galileo, it will be recalled, observed the isochronism of the pendulum but he never succeeded in applying the pendulum to any of the various weight-driven or spring-driven clocks which were then in vogue and were such poor time keepers that their makers placed an hour hand on the central shaft but did not consider it worth while to attach a minute hand.

Huygens, in 1656, succeeded in taking the crown wheel and verge of the older clocks and applying a pendulum to the verge in such a way as to control its motion, while at the same time the pendulum received through the verge an impulse which though small was sufficient to maintain the motion of the pendulum. In 1657, this device was patented. From 1658 on, all new clocks were built with pendulum regulation. Almost every year since then has seen some new improvement in the mechanism of the clock, until at the present time a first class Riefler clock will maintain its rate constant within 0.02 of a second during a month. So fundamental, however, was the patent of Huygens that Professor W. I. Milham, an acknowledged authority upon this subject, says:

> "It will be seen that from 1360 when the first unquestioned mechanical clock was produced by DeVick until 1658 there were practically no changes or improvements in clock mechanism. In less than one century following 1658 all these radical improvements were introduced and the clock became practically the clock of to-day. The last one hundred and fifty years have seen only minor changes, constantly improved workmanship, and a steady increase in the time-keeping accuracy. All this applies of course only to pendulum-controlled clocks."[11]

The measure of centripetal force

Huygens' profound study of the pendulum led him to the conclusion that a pendulum is *perfectly* isochronous if the point of suspension coincides with the point where two cycloidal jaws meet, so that as the pendulum vibrates, the suspending thread wraps itself against first one, then the other of these jaws.

As a mere incident to this discussion, Huygens considered the problem of uniform circular motion. It is hardly thinkable that man from the earliest days of civilization was not perfectly familiar with the pull which it is necessary to exert upon any heavy object which one may swing in a circle about his head; and yet no one up to the middle of the seventeenth century had determined the factors upon which the amount of this pull depends.

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[11] *Time and Timekeepers*, p. 148.

The following paragraph occurs in a letter from Huygens to Oldenburg, Secretary of the Royal Society of London, dated September 4, 1669:

> "I send you herewith appended, some anagrams which I will be pleased to have you keep in the registers of the Royal Society, which has been so kind as to approve this method of mine for avoiding disputes, and for rendering to each individual that which is rightly his in the invention of new things."

Of the fourteen anagrams enclosed, two give the essential theorems concerning the amount of the centripetal force. One of these will suffice to illustrate a current method of that period. Each line of figures represents a line in the Latin theorem and each figure denotes the number of times which the letter immediately above it appears in that line.

A transliteration of these anagrams first appeared in Huygens' memorable volume of *Horologium Oscillatorium, sive de Motu Pendulorum ad Horologia adapto* (Paris, 1673).

(i) Anagram of 1669 (*Oeuvres*, vi, p. 487):

a b c d e f g h i l m n o p q r s t u x y z
3 0 6 0 7 1 0 0 5 1 3 2 3 2 0 6 3 4 4 1
9 0 1 3 5 1 2 0 6 1 5 2 0 0 2 4 0 6 5 0

(ii) Latin of 1673 (slightly different from that of 1669): Si mobile in circumferentia circuli feratur ea celeritate, quam acquirit cadendo ex altitudine, quae sit quarti parti diametri aequalis; habebit vim centrifugam suae gravitati aequalem; hoc est, eadem vi funem quo in centro detinetur intendet, atque cum ex eo suspensum est.

(iii) English translation: If a body traverse a circumference with the same speed which it would gain in falling from a height equal to one quarter the diameter, the centrifugal force then acting upon the body will be equal to the pull of gravity upon it: i.e., it stretches the cord which retains it just as much as if the body were suspended by this cord.

(iv) Modern point of view: Let F_c denote the centripetal force acting upon a particle of mass m, moving in a circle of radius r; and let $F_c = mg$. Now g is measured by speed of fall, namely, $v^2 = 2gh$. Hence, if the height of the fall be one half the radius of the circle, then $v^2 = 2g\frac{r}{2}$; and hence $F_c = \frac{mv^2}{r}$, which is the fundamental theorem concerning centripetal force.

The unfortunate expression "centrifugal force" which first creeps into English in the *Principia* of Newton arises in a transfer of thought from the pull upon rotating particle to the reaction on the hand which is pulling the string. One who has in mind the first law of motion and who "keeps his eye on the ball," as suggested by Dr. Gordon S. Fulcher, will find no use for the phrase "centrifugal force."

The introduction of the idea of dynamical mass

One of the earliest conceptions of physics is the notion of gravitational mass, i.e., mass as determined by the balance. Coins were introduced about the seventh century B.C.; and probably as a time-saving device; for, previous to this time, money was counted by use of the balance. Thus, in *Genesis*, xxiii, 16, one finds that "Abraham weighed to Ephron the silver which he had named in the audience of the sons of Heth, four hundred shekels of silver, current money with the merchant." Still more ancient balances are pictured on the tombs of the Egyptians; but in all these cases, including the modern chemical balance, what is determined is the pull of the earth upon a certain body, and hence its gravitational mass.

Aristotle observed that a loaded balance swings more slowly than an empty one; and he must therefore have had a faint adumbration, at least, of dynamical mass; so also had any lad of ancient or modern days who in walking along a level road may have stumped his toe against a brick. But the earliest quantitative conception of this idea is, so far as the author has been able to discover, found in Huygens' discussion of centripetal force which was essentially complete in 1673, but which first appeared in his posthumous publication *De vi centrifuga*, 1703. After having proved the various theorems concerning the centripetal acceleration—purely kinematic theorems—he then suddenly (p. 407) digresses to say that in the case of particles moving along equal circles with equal speeds the centripetal forces are to each other as "the weights of the particles" or as their "solid quantities," *sicut mobilium gravitates seu quantitates solidas.*

This phrase *solid quantity* is perhaps the earliest expression other than *weight* to indicate what Newton and all his successors have called *mass*. When the circular motion under consideration was horizontal, Huygens doubtless instantly realized that weight was in no way involved. The measure of this "solid quantity," m, is naturally obtained by use of the simple equation just derived, namely, $m = \frac{F_c}{v^2/r}$ where F_c would, in Huygens' day, be measured in pounds and ounces.

The next bit of light which was shed upon this subject seems also to have been furnished by Huygens; for it was upon his suggestion that Jean Richer (date of birth unknown, died 1696) went to Cayenne in South America in 1671, and made observations there, in 1672, on the length of the seconds pendulum. His result was that a pendulum beating seconds at the equator is very nearly one-eighth inch shorter than a seconds-pendulum at Paris. Now since $T = 2\pi\sqrt{l/g}$, it is evident that the length of a seconds pendulum varies directly as the acceleration of gravity; and hence that gravity is less at the equator than at Paris; in other words the weight of a given rigid pendulum is less at the equator than at Paris. But, as the pendulum is carried from one of these places to the other, it must have been evident to Huygens and Richer that there was *something* about the pendulum that remained constant.[12] And that something is precisely what we understand today by *mass.* Just how recently this work has been done may be realized from the fact, that at the same time (1673) when Richer was at work at Cayenne, Marquette and Joliet were threading their way across Wisconsin from Green Bay, near Lake Michigan, *via* Portage to Prairie du Chien.

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[12] These experiments of Richer are described in the *Mémoires de l'Academie Royale des Sciences*, p. 233, in particular, p. 320. Edition of Paris, 1729. Newton also describes his work in the *Principia*, Proposition XX, Problem, IV.

The next appearance of the idea of mass in the literature of physics seems to be in the first paragraph of Newton's *Principia* which reads as follows:

> "DEFINITION I
>
> *"The quantity of matter is the measure of the same, arising from its density and bulk, conjointly."*
>
> "Thus air of a double density, in a double space, is quadruple in quantity; in a triple space, sextuple in quantity. The same thing is to be understood of snow and fine dust or powders that are condensed by compression or liquefaction; and of all bodies that are by any causes whatever differently condensed. I have no regard in this place to a medium, if any such there is, that freely pervades the interstices between the parts of bodies. It is this quantity that I mean hereafter everywhere under the name of body or mass. And the same is known by the weight of each body; for it is proportional to the weight, as I have found by experiments on pendulums, very accurately made, which shall be shown hereafter."

It is this definition of Newton's which is expressed in the modern way by the equation $M = VD$, where M denotes the mass, V, the volume, and D, the average density of the body in question. Since the present generation defines density by use of this equation and one equation cannot be used to define two different quantities, some writers[13] have spoken of the paragraph just quoted from

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[13] Hoppe, *Geschichte der Physik*, p. 61, 1926.

Newton as an *argumentum in circulo.* This however is a very hasty conclusion; for in the time of Newton, *density* and *specific gravity*, were employed as synonyms, and the density of water was taken arbitrarily to be unity. The three fundamental units employed in the above quotation were therefore, *density*, *length*, and *time*, instead of our *mass*, *length*, and *time.* On such a system, it is both natural and logically permissible to define *mass* in terms of *density.*

Newton proceeded to repeat the hollow pendulum experiment of Galileo, in which the bob of the pendulum was filled in succession with various substances, such as lead, gold, silver, tin, brass. He argued as follows: Let m be the mass of the pendulum and W its weight. Then the equation of the pendulum may be written

$$T = 2\pi\sqrt{\frac{l}{g}} = 2\pi\sqrt{\frac{l}{(W/m)}} = 2\pi\sqrt{\frac{m\,l}{W}}$$

whence

$$\frac{W}{m} = \frac{4\pi^2 l}{T^2}$$

If now the length of the pendulum be kept constant, as can be done by properly placing the various substances in the hollow pendulum-bob, any variation of $\frac{W}{m}$ will exhibit itself as a variation of the period, T. No such variation was discovered by Newton and he therefore concluded that *mass* and *weight* are proportional.[14] Again in 1832 this experiment was repeated by Bessel, the eminent German astronomer, at the Königsberg Observatory, with greater accuracy, but with the same result.[15]

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[14] *Principia*, Book III, Proposition VI.

Since it has recently been shown that radioactive substances possess large quantities of intraatomic energy and since energy is now known to possess inertia in an amount defined by the equation $E = m\, c^2$ where E denotes energy, m, inertia, and c the speed of light, it was suggested by Sir J. J. Thomson in his presidential address before the British Association for the Advancement of Science at Winnipeg that the ratio of mass to weight for radioactive substances, such as uranium oxide, might differ in value from the ratio for ordinary substances. Extra energy carries with it extra inertia. Query, does this extra *inertia* add anything to the *weight* of the body? Uranium oxide contains about 85 per cent uranium and supposedly about 80 per cent radium; does it therefore possess a larger mass than an equal weight of some non-radioactive substance?

Mr. L. Southerns in the Cavendish Laboratory put this question to nature by comparing the periods of two pendulums, one having a bob filled with two pounds of uranium oxide, the other with an equal weight of lead oxide. After performing the experiment with every precaution and many clever devices,[16] he concludes that if there is any variation in the ratio of mass to weight it is less than one part in 200,000—which is very much less than that predicted by theory. All experimental evidence appears to indicate that under ordinary terrestrial conditions, the gravitational or astronomical mass of a body is identical with its dynamical mass.

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[15] *Poggendorff's Annalen*, 25, p. 414, 1832.

[16] *Proceedings of the Royal Society* A., 84, p. 325, 1910.

From what precedes it would seem fair to conclude that the idea of mass was first definitely conceived by Huygens and later perfected by Newton.

The compound pendulum

The importance of the pendulum, vibrating about a horizontal axis in consequence of its own weight, as the simplest of periodic phenomena, was early recognized; and the early students of this subject also realized that there must be some particle in any physical pendulum which, if it were free from all other particles in the pendulum, would vibrate about the same axis with the same frequency as the actual pendulum. The first man who succeeded in locating this point—which he called the center of oscillation—was Christiaan Huygens. His solution is given in Part IV of his memorable book.[17] The result is contained in his *Proposition VI* which is essentially the following: The length of the equivalent simple pendulum is obtained by taking the sum of the mass of each particle of the pendulum by the square of its distance from the axis of rotation and dividing this sum by the product of the weight of the pendulum by the distance of its center of gravity from the axis of rotation. Or, in more modern terminology,

$$T = 2\pi \sqrt{\frac{\Sigma\,(m\,r^2)}{M\,g\,a}}; \text{ and } l = \frac{\Sigma\,(m\,r^2)}{M\,a}$$

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[17] *Horologium Oscillatorium,* Paris, 1673.

where T is the period of the pendulum; l, the length of the equivalent simple pendulum; m, the mass of any particle of the pendulum; r, its distance from the axis of rotation; M, the total mass of the pendulum, and a, the distance of the center of gravity of the pendulum from the axis of rotation.

The whole demonstration is based upon the two following hypotheses: (i) If any system of masses is set in motion by its own weight, its center of gravity never rises higher than it was at the beginning of the motion; (ii) when the air and every other form of resistance is removed, the center of gravity of a pendulum swings through equal arcs during its ascent and its descent.

These two assumptions are practically equivalent to the law of the conservation of energy when limited to purely dynamical processes; for the ideas of *work* and *velocity* are at the bottom of each.

It is difficult for us, at this late date, to realize how great a stride was made by Huygens when he discovered how, by simply weighing and measuring a given body, say a lath, one could sit down and compute its period of vibration when suspended about any particular line as axis.

The problem of a freely falling body, solved by Galileo, is the first great solution in dynamics; that of the physical pendulum by Huygens is the second and an immensely more difficult one. It was in fact the first dynamical system, as distinguished from a particle, to be studied. It was too complex for Galileo; and it was a stumbling block to Descartes; but perplexity is the beginning of knowledge. Some of the most important concepts and principles of dynamics center about the pendulum.

Thirty years after Huygens' solution, James Bernoulli (1703) proved that the center of percussion is identical with the center of oscillation. Huygens used an energy method; Bernoulli, a statical method.

Mechanics is in a peculiar sense an Italian science. Its first and simplest chapter—Statics—was written by Archimedes in Sicily. Its earliest applications to engineering were made by Vitruvius, Frontinus, and Leonardo da Vinci. Its second and most fundamental chapter—Dynamics—was written by Galileo who conceived the idea of acceleration as the criterion of force. The final chapter (in a certain sense; in the true sense, there is no final chapter in science) of classical mechanics was written by Lagrange, a native of Turin. The pendulum is the first great dynamical problem solved outside of Italy.

Impulsive forces

The predecessors of Huygens and Newton were exceedingly puzzled by the problem of describing what happens when two bodies, such as a ball and a bat, collide. Galileo's language is far from clear when he discusses these questions. Collisions between two moving bodies fall into three groups:

(i) Impacts between inelastic bodies, such as two balls of clay.

(ii) Impacts between perfectly elastic bodies—a case which is very nearly represented by the collision of two ivory billiard balls.

(iii) Impacts between imperfectly elastic bodies, as, for example, two wooden balls. Strictly speaking this third case includes, of course, all the cases actually occurring in nature.

The first of these three cases was solved by John Wallis (1616–1703) in a paper presented to the Royal Society of London in November, 1668. In December of the same year, Sir Christopher Wren (1632–1723) presented to this society a solution of the second case; while Huygens in the January following also presented without proof and independently of Wren, the laws governing the second case. The solution for the general case (iii) is given by Newton in the *Principia* (page 92 of Motte's translation) and may be stated as follows: *When two bodies collide the relative velocities of their centers of gravity after collision is equal to ϵ times the relative velocity before collision and is opposite in direction.* This experimental law of Newton's, together with the fact that *the momentum of the system is not changed by collision*, completes the description. The case solved by Wallis is obtained by putting the coefficient of elasticity, $\epsilon = 0$. For case (ii) $\epsilon = 1$; while for case (iii) $1 > \epsilon > 0$. In terms of algebra these two laws would read as follows: Let m and m' denote the masses of the colliding bodies. Let u and u' be their respective velocities along any one direction *before* impact and v and v' their velocities after impact. Then

$$v - v' = - \epsilon (u - u')$$

and

$$m v + m' v' = m u + m' u'$$

These two equations of Newton are always competent to give the value of each of the unknown quantities, v and v'.

Huygens' paper on collision which first appeared in his posthumous volume (1703) is now easily available in Ostwald's *Klassiker der exacten Wissenschaften*, No. 138.

We pass now to the dynamical advances made by the third member of this great trio,

SIR ISAAC NEWTON, 1642–1727

The main facts of his life which are something like the following are already familiar to most readers. Born at Woolsthorpe near the east coast of England, midway between London and York, on December 25, 1642 (o.s). He received his elementary education at the grammar school in Grantham where he early showed great aptitude in making kites, windmills and other mechanical toys. On July 8, 1661, he matriculated at Trinity College, Cambridge; and graduated B.A. in January, 1665. It was in this year probably—the year in which he was driven out of Cambridge by the plague—that the idea of fluxions—infinitesimal calculus—first occurred to him. In 1667 he was elected to a fellowship in Trinity College and took his degree of M.A. in the year following. In 1669, he was appointed to the Lucasian professorship in Cambridge, the chair now occupied by Sir Joseph Larmor. The year 1687 was made memorable by the publication of his monumental volume, the *Principia*. After his appointment to the post of warden of the mint in 1694, and to the mastership of the mint in 1697, he still retained his professorship and held his lectures at Cambridge until 1701 when he resigned both his chair and his fellowship. The Royal Society elected Newton to its presidency in 1703 and reelected him annually during the remaining twenty-four years of his life. Queen Anne in 1705 held a court at Cambridge and there conferred the order of knighthood upon Newton. Later Newton's company was much sought after by the court of George I. On February 28, 1727, when Benjamin Franklin was a printer's boy in London, Newton presided at a meeting of the Royal Society. He died on March 20 following and was buried in Westminster Abbey.[18]

Returning now from this biographical digression to our dynamical indebtedness to Newton, we shall first summarize the steps which had already been taken:

(i) The two fundamental principles of statics—moments and the inclined plane—had been established by Archimedes, Stevin, and others; and had been subsumed to a certain extent under the single principle of virtual displacements.

(ii) Galileo had enunciated the first two of the three laws of motion and explained force as the time variation of momentum.

(iii) Huygens had introduced the idea of mass and formulated the laws of centripetal force.

To these Newton added what is known as the third Law of Motion which Andrew Motte in 1729 translates as follows from the Latin of the *Principia*.

> LAW III: *To every action there is always opposed an equal reaction; or the mutual actions of any two bodies upon each other are always equal, and directed to contrary parts.*

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[18] The reader who desires a thoroughly modern and authoritative picture of Newton will find it in *Nature*, 119, Supplement 26, March, 1927, where the bicentenary addresses delivered at Grantham by J. J. Thomson, Lamb, Glazehook, Marvin and others are reprinted.

The competence of these three laws in the description of the effects of force and in giving the equations of motion for practically all the problems of mechanics is a matter of unceasing surprise. This Third Law, it will be observed, underlies Newton's treatment of the collision of bodies mentioned above.

The achievement, however, for which Newton is best known is doubtless the explanation which he gave of Kepler's laws of planetary motion and Galileo's laws of falling bodies. From Kepler's law of constant areas, he showed that the force acting upon a planet or satellite is not from the back of the planet—not a *vis a tergo*—but is a force directed toward the focus of the planet's elliptical path. From the shape of the orbit—an ellipse—he proved that this attractive force varies inversely as the square of the distance between sun and planet or earth and moon; while from Kepler's third law he inferred that the force of attraction between the planet and sun is proportional to the mass of the planet, the constant of proportionality being the same for all of the planets. In addition to this, he concluded that, unless there be something more peculiar than mere size in the mass of the sun, this attraction must be proportional also to the mass of the sun; all of which is summarized in his justly celebrated law of inverse squares, namely,

$$\text{Force of attraction} = G\,\frac{m\,m'}{r^2}$$

where G is a numerical constant depending for its value upon the units employed in measuring masses and distances. The weight of a body from this time (1687) on became merely the attraction of the earth for that body minus the centripetal force required to hold the body in its circular path about the axis of the earth.

Shortly after Newton's time the law of inverse squares was found to hold for electrostatic and magnetostatic attractions; so that for more than 200 years—up, indeed, to the time of J. J. Thomson, Einstein, Rutherford, and Bohr—Newton's description of planetary motion remained a norm for all kinds of dynamical explanations, including such molecular phenomena as the surface tension of liquids and the elasticity of solids. The problem of the tides—the great riddle which the ancients had connected with the moon and left there—was first solved by Newton, who showed that the explanation in terms of the inverse square law is both simple and natural. It was nearly a century later that Laplace (1749–1827) completed and perfected the Newtonian treatment of the tides.

In like manner, the precession of the equinoxes fell into line and showed itself to be simply an effect of the torque which the moon exerts upon the equatorial protuberance of the earth, thus being a special case under the second law of motion and the law of universal gravitation. Another illustration of the tremendous fruitfulness of the laws of motion and gravitation is the following theorem which is in constant use in electrostatics and astronomy.

The field of force, produced by a uniform hollow spherical shell is, for a point in the interior, always zero; while for an exterior point it is the same as would be produced by the entire mass of the shell concentrated in a single particle at the center. This powerful theorem, considered by some to be Newton's most important contribution, taught the world that the various masses which constitute the sun, moon, and earth act as if they were heavy mathematical points situated at the respective centers of these bodies.

In regard to the still unsolved problem of gravitation, it is important to bear in mind Newton's attitude of mind which he clearly sets forth, as follows, on the last page of the *Principia:*

> "Hitherto we have explained the phaenomena of the heavens and of our sea by the power of gravity, but have not yet assigned the cause of this power. This is certain, that it must proceed from a cause that penetrates to the very centres of the sun and planets, without suffering the least diminution of its force; that operates not according to the quantity of the surfaces of the particles upon which it acts (as mechanical causes use to do), but according to the quantity of the solid matter which they contain, and propagates its virtue on all sides to immense distances, decreasing always in the duplicate proportion of the distances. * * * But hitherto I have not been able to discover the cause of those properties of gravity from phaenomena, and I frame no hypotheses."

Comparing the work of Newton with that of Galileo, Norman Campbell puts the matter as follows:

> "As Galileo was the founder of experimental physics, so Newton was the founder of theoretical physics; as Galileo first introduced the type of law which has become most characteristic of the science, so Newton introduced first the characteristic type of theory. And of the two Newton is rightly judged by popular opinion to have been the greater man. But it is not rightly recognized how great was the achievement of Galileo; indeed his fame is usually associated with things—the observation of the isochronism of the pendulum, or his fight with clericalism over the Copernican theory—other than with his greatest service to science. It is his establishment of the first

PIETER VAN MUSSCHENBROEK (1692–1761)
Pioneer in the presentation of experimental physics. Professor of Mathematics in the University of Leiden

experimental numerical law that constitutes his highest claim to greatness, and that law was as much an expression of his personality as the theory of Newton."[19]

But Mechanics, even in the advanced form in which Newton left it, was far from its modern form. Many important steps remained to be taken. Two of these call for brief notice.

The first of these two steps was to disentangle the ideas of *force*, *momentum*, and *energy;* the second was to introduce a practicable nomenclature.

THE FAMOUS DEBATE OF THE CARTESIANS AND LEIBNITZIANS

The value of any discussion lies largely in the opportunity which it furnishes the participants for the clarification of thought; and, in this respect, the bitter discussion between the adherents of Leibnitz (1646–1716) on the one hand and of Descartes (1596–1650) on the other—a dispute which raged for more than half a century and which was first composed by d'Alembert (1717–1783) when he published his *Traité de dynamique* in 1743,—must be ranked as one of high value.

Descartes' argument, in modern terminology, is as follows: If you wish to compare two forces F_1 and F_2, allow them to act for any given time t upon two masses m_1 and m_2 respectively; then the ratio of these forces will be the ratio of the momenta generated in these two bodies. Or, in symbols,

$$F_1/F_2 = \frac{m_1\, a_1}{m_2\, a_2} = \frac{m_1\, a_1\, t}{m_2\, a_2\, t} = \frac{m_1\, v_1}{m_2\, v_2}$$

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[19] *What is Science?* p. 94.

In other words, the measure of force is the momentum which it generates.

Leibnitz on the other hand based his opinion upon the common experience that it requires the same "force" (as he called it) to raise a body weighing m pounds through a height of $4\ h$ feet as it does to lift a body of $4\ m$ pounds through a height of h feet. Now it is well known, argues Leibnitz, that a body in falling through $4\ h$ feet acquires a velocity just twice as great as when it falls through h feet; and hence if the "force" required is the same in each of the two cases just mentioned, this "force" must be measured by the product of the "body" (mass) by the square of the speed—a product to which Leibnitz, in 1695, gave the name *vis viva*, reserving the term *vis mortua* for the forces which occur in statics. In symbols Leibnitz's viewpoint is as follows: Let s be any given distance; then

$$F_1/F_2 = \frac{m_1\ a_1}{m_2\ a_2} = \frac{m_1\ a_1\ s}{m_2\ a_2\ s}$$

But a body moving under an acceleration a will traverse a distance s provided its speed v has the following value, $v^2 = 2as$. Hence the ratio of the forces becomes

$$F_1/F_2 = m_1\ v_1^2/m_2\ v_2^2$$

In other words the measure of force is not its momentum but its *vis viva.*

The fundamental question thus raised was completely answered by d'Alembert in the Discours Préliminaire (p. xvii) of his *Traité de Dynamique.* He explains why he does not discuss the problem in the text of his work and then says:

> "It is for this reason that I have not deemed it wise to enter upon the discussion of the famous question of *vis viva.*
>
> "This problem upon which geometers have been divided for thirty years consists in determining whether the force of a body in motion is proportional to the product of the mass by the velocity or to the product of the mass by the *square* of the velocity; whether, for example, a body (*corps*) which is twice as large as another and has three times the speed of the other, will have 18 times as much force or only 6 times as much. In spite of the debates to which this question has given rise, its complete uselessness in the science of Mechanics has prevented me from making any mention of it in the body of this work. However I hardly feel like passing over in silence an idea which Leibnitz thought it an honor to have discovered, which the great Bernoulli afterwards investigated so thoroughly, which Maclaurin made every effort to overthrow, and in which a number of distinguished mathematicians have succeeded in interesting the public. Accordingly I shall omit wearisome detail and shall explain, very briefly, the principles which underlie the solution of this problem.
>
> "When one speaks of 'the force of a body in motion,'' either he does not attach to the expression any definite idea or he understands by it only the property which moving bodies have of overcoming obstacles which they encounter or of resisting them. It is then neither by the space which a body traverses uniformly, nor by the time spent in traversing it, nor by the simple, unique, and abstract consideration of mass and velocity that one is to estimate a force; it is only by the obstacles which a body encounters and by the resistance which these obstacles offer. The greater the obstacle which a body can overcome, or which it is able to resist, so much the greater is the *force* said to be, it being understood that the word 'force' does not imply any being resident in the body, but is merely a brief description of a fact, just as when it is said that one body has twice the *speed* of another, instead of saying that in equal times one traverses twice the distance of the other, no pretence is made of

implying that the word '*speed*' represents anything existing in the body.* * *

"Now the whole world is agreed that there is equilibrium between two bodies when the products of their masses by their respective virtual velocities (i.e., the velocities with which they approach each other) are equal. Hence in the case of equilibrium the product of the mass by the velocity, or what is the same thing, the quantity of motion represents the force. All the world is *also* agreed that, *in the case of retarded motion*, the number of obstacles overcome is as the *square* of the velocity; so that a body which, with a given speed, has compressed a certain spring will, with double this speed, be able to compress, either simultaneously or successively, not two, but four such springs; with triple speed it will compress nine such springs, and so on."

The upshot of this entire discussion was to establish *vis viva* as a measure of *force acting through a certain distance*, and *momentum* as a measure of *force acting through a certain interval of time*, yielding us the two fundamental and thoroughly consistent definitions of force which are today everywhere used in physics, namely, the *space variation of energy* and the *time variation of momentum.*

Except for the unfortunate dropping of the factor "1/2" from the expression for *vis viva*, the world by this time had a fairly clear grasp of the ideas of *force*, *momentum*, *energy*, and *work*. It was still during the life-time of d'Alembert that the French Academy resolved (1775) not to receive any more schemes for perpetual motion, so fully did they appreciate the fact that *vis viva* is uncreatable. The "conservation of *vis viva*" is a term due to John Bernoulli (1729); but the word "energy" makes its first appearance nearly a century later when Thomas Young, the eminent English physicist, uses it in his

Lectures on Natural Philosophy, vol. 2, p. 52, where he gives the following "DEFINITION: The product of the mass of a body into the square of its velocity may properly be termed its *energy*." How incomplete this definition is will be seen from the fact that it includes only the mechanical energy of motion and omits the factor "1/2" just as Leibnitz did when comparing two forces. The "1/2" reappears as soon as one considers the energy of motion spent in lifting the body through a height. The name "potential energy" is due to the Scottish engineer, W. J. M. Rankine (1820–1872).[20]

The term "work," in its modern sense, is little more than a century old. It was suggested to Poncelet, a distinguished French engineer, by Coriolis, a French physicist, about the year 1826. From this date on, various forms of energy other than kinetic were rapidly recognized. Sadi Carnot,[21] in 1824, applied the energy equation for the first time to a non-mechanical phenomenon, namely, heat; and thus began the great chapters on the Nature of Heat and the Conservation of Energy which have been written into modern physics and which we shall consider later.

THE NOMENCLATURE OF MECHANICS

We pass now to the second of the two steps above noted as necessary to bring mechanics into its modern form.

The use of three coördinates to represent a point in space appears first to have been adopted by A. Parent in

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[20] See his *Scientific Papers*, p. 203, 1881.

[21] *Reflexions sur la puissance motrice du feu*, Paris, 1824.

1700 who thus derives the equation to the sphere referred to its center.[22] The earliest resolution of forces along the axes of X and Y is found, however, in Colin Maclaurin's *Treatise on Fluxions.*[23] Here a force is represented by a straight line and its components are written $\ddot{x}$ and $\ddot{y}$ after the manner of Newton.

Euler, (1707–1783) the great Swiss mathematician in his *Theory of the Motion of Rigid Bodies* (1765) resolves forces along three mutually perpendicular axes X, Y, and Z and obtains the following equations of motion for a particle.

$$ddx = \frac{2\,g\,P\,dt^2}{A};\; ddy = \frac{2\,g\,Q\,dt^2}{A};\; ddz = \frac{2\,g\,R\,dt^2}{A}$$

where A is defined as the weight (*pondus*) of the particle and g as the distance through which it will fall freely in one second at that particular locality. Hence Euler's $\frac{A}{2g}$ is equivalent to the modern mass of the particle, and his equations are nothing else than our respective mass-accelerations of the three components of a force.

$$m\frac{d^2x}{dt^2} = P \qquad m\frac{d^2y}{dt^2} = Q \qquad m\frac{d^2z}{dt^2} = R$$

We are not here considering Euler's great contributions to dynamics such as his study of vibrating strings, his equations of motion for a planet or a top, or his equations of motion for fluids, but simply the great convenience which he gave to dynamics by changing it from the synthetic form of Newton into the vastly simpler analytical form which we use at present; simpler because when vectors are resolved into rectangular components, they can be added scalarly.

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[22] *Encyclopaedia of the Science of Mathematics,* T. III, vol. 4, Fasc. I, p. 2.

[23] Sections 465, 466, 884. First edition, Edinburgh, 1742, Second edition, London, 1801.

The perspective would not be right if this great trio, Galileo, Huygens and Newton, were left without a few words about Varignon and d'Alembert, the former a contemporary, the latter a successor, of Newton.

VARIGNON

The service of Varignon (1654–1722), an able French mathematician, lies mainly in the fact that he explained in the clearest possible manner the addition and subtract tion of vectors. His first exposition[24] appeared in the same year with Newton's *Principia.* It is therefore a thoroughly independent and original piece of work, containing the dynamical explanation of practically every kind of machine then in use. The completed work appeared in two posthumous volumes in 1725, under the title *Nouvelle Mécanique.* In the library of Northwestern University is a copy of this work which formerly belonged to Augustus De Morgan (1806–1871), the eminent English mathematician and father of William De Morgan, the novelist. On the flyleaf of the first volume, one finds the following characteristic autographic note.

"This work was born long after its own death and three years after the author's. The *Projet* in 1687 enabled all the world to act upon it so that when the finished work was published, it had long been superseded. See 'Varignon' in Penny Cyclopedia.

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[24] *Projet d'une nouvelle Mécanique,* Paris, 1687.

"The great feature of this work, as of the *Projet*, is the prominence given to the composition of forces. Varignon and Newton were forcing this commodity into the market at the same time and independently.

A. de Morgan."

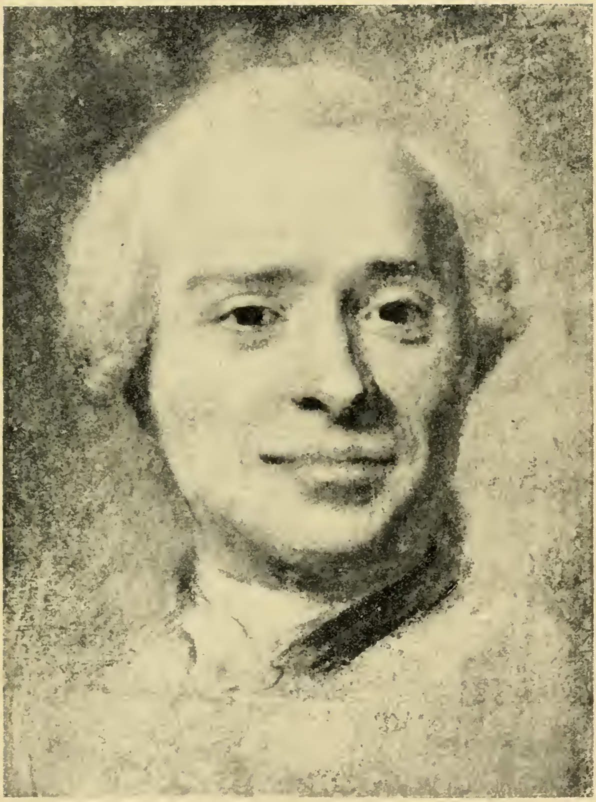
Sept. 8/61.

It will be at once evident that Varignon's contributions were not of the epoch-making type; but they did much to prepare the science of mechanics as a tool for the engineer.

D'ALEMBERT, 1717–1783, AND HIS PRINCIPLE

In the year 1730, there matriculated in the College Mazarin where Varignon had long held a professorship, a small lad who, only thirteen years before, had been picked up as a waif, a foundling, abandoned near the church of St. Jean le Rond in Paris. In college he studied first theology, then law, and later medicine; but last of all he took up the subject of mathematics under himself as a tutor. During his early years, he was known as Jean le Rond; but later he assumed the name of d'Alembert and so rapidly proceeded to immortalize it that, at the age of twenty-four (1741), he was received as a member into the Academy of Sciences. Within two years appeared his famous *Traitê de dynamique* (1743) enunciating what is now known as "d'Alembert's Principle," a point of view which is so important that we are led at this point to consider the life and work of its author.

The catholicity of taste and talent which d'Alembert exhibited during his student days marked his entire life;



Jean le Rond d'Alembert (1717–1783)
French mathematician, dynamicist, and philosopher

accordingly his researches cover such diverse fields as fluid motion, vibrating strings, planetary motion, much work on the great French *Dictionnaire Encyclopédique*, a translation of *Tacitus*, a *Histoire des membres de l'Academie française*, the *Élements de musique théorétique et practique*, *Elements de Philosophie* and a treatise *Sur la destruction des Jesuits.* Frederick the Great, tried in vain to capture him for the presidency of the Berlin Academy. He was the warm friend of Voltaire and so highly thought of by David Hume that the latter left him a thousand dollars in his will. d'Alembert lived at a time when the leading mathematicians, such as Euler, the Bernoullis and Clairault, were saturated, so to speak, with dynamical ideas. These men worked and thought in terms of the concrete and the physical to a much greater extent than mathematicians have ever since done.

The principle which goes by d'Alembert's name is based upon Newton's third law of motion. It is most easily comprehended by considering a body whose motion is uniplanar. Let any particle of the body have a mass m; and suppose this particle to be acted upon by external forces X and Y, which d'Alembert calls "impressed forces." Let the internal forces, arising, say, from cohesion, be denoted by P and Q. Then if x and y denote the coördinates of the particle m, the equations of motion—one set for translation and one for rotation—become

$$\text{(i)} \qquad X + P - m\frac{d^2x}{dt^2} = 0 \qquad\qquad Y + Q - m\frac{d^2y}{dt^2} = 0.$$

$$\text{(ii)} \qquad (xY - yX) + (xQ - yP) - m\left(x\frac{d^2y}{dt^2} - y\frac{d^2x}{dt^2}\right) = 0.$$

d'Alembert next points out that since all the internal forces are in equilibrium among themselves, one may write

$$\Sigma P = \Sigma Q = 0$$

and

$$\Sigma (xQ - yP) = 0$$

Hence the equations of motion for the entire body reduce to

$$\Sigma \left(m \frac{d^2x}{dt^2} \right) - \Sigma X = 0 \qquad \Sigma \left(m \frac{d^2y}{dt^2} \right) - \Sigma Y = 0$$

and

$$\Sigma m \left(x \frac{d^2y}{dt^2} - y \frac{d^2x}{dt^2} \right) - \Sigma (xY - yX) = 0$$

These last equations are the ones employed in the solution of practically every dynamical problem.

d'Alembert's contribution is twofold; first, he formulates the fact that the internal stresses balance each other and can therefore be neglected; second, he introduces the mass accelerations with a negative sign—what he calls the "reversed effective forces"—and thus reduces every dynamical problem to one of statics. d'Alembert puts his principle into words on page 74 of his *Traité de Dynamique;* but the statement is somewhat lengthy. The following English form is simpler and clearer: (i) In any system of bodies acting one upon the other, the *impressed forces* when compounded with the *reversed forces of inertia* form a system in equilibrium. (ii) The *internal* or cohesive forces also form a system in equilibrium. It is to d'Alembert, therefore, that we owe the fundamental equations of modern dynamics.

CHAPTER VI

REFRACTION, DISPERSION, AND THE NATURE OF LIGHT

SNELL'S LAW

> "If we wish to erect new structures we must have definite knowledge of the old foundations."
>
> —CALVIN COOLIDGE, *Inaugural Address*, 1925.

The manner in which medieval optics suffered from want of the law of refraction has been indicated in an earlier chapter. The correct statement of this law was first given by Willebrord Snell (1591–1626) of the University of Leyden in 1621, in an unpublished paper. In Snell's manuscript, the matter was expressed essentially as follows: Let any plane refracting surface be indicated by its trace DE; and draw ON normal to this surface. Then if BO indicates the direction of the incident ray and CO that of the refracted ray, it is found that the ratio of the two intercepts AC and AB (drawn parallel to the normal ON) is a constant. In other words,

$$\frac{AC}{AB} = \frac{\text{cosecant } r}{\text{cosecant } i},$$

where i and r are the angles of incidence and refraction respectively. It was an easy matter for a profound mathematician such as Descartes to transform Snell's ratio of two sines into the modern form.

$$\frac{\sin i}{\sin r} = \text{constant} = n$$

Descartes prefaced his statement of this law with a long mechanical explanation of the nature of light and of matter which has little interest for modern students, since his reasoning was almost immediately shown by Fermat and others to be without any basis in experiment; and, indeed, contrary to experiment. Descartes' account of the whole matter will be found in the second Discours of his *Dioptrique* which is one of the *essais* published in illustration of the ideas which he advocated in his great work *Discours de la Méthode*.[1]

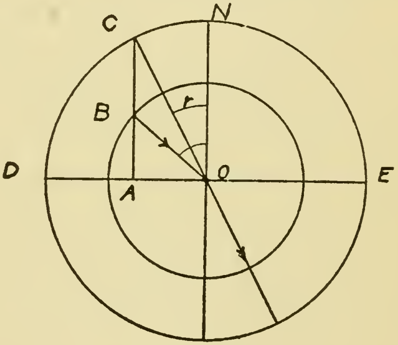


Fig. 6. Snell's Law of Refraction

The weak point in Descartes' argument is that he assumes light to travel more rapidly in denser media. Fermat (1601–1665) proceeded to show how by making just the opposite assumption, namely, that light travels more *slowly* in denser media, one could arrive at the true law of refraction. The principle which Fermat employed and which had been adumbrated by Hero of Alexandria, is that a ray of light originating at a point A in one medium will travel to a point B in another medium by a path which requires a minimum of time.

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[1] *Oeuvres*, VI, pp. 93–105; edited by Adam and Tannery, Paris, 1902.

Snell's law was by this time well established; but it was most elegantly demonstrated, in 1690, by Huygens in his *Traité de la Lumière*, where he assumes only that the speed of light changes in passing from one medium to the other and proceeds to show that under these circumstances the refractive index must represent the inverse ratio of these two speeds. Hence when the law is written, as at present, $n \sin i = n' \sin i' = \textit{invariant}.$ n/n' = speed in second medium/speed in first medium.

Newton, in the meantime (1687), had derived Snell's law by a set of assumptions made to fit his theory that light consists of small material particles which again move more rapidly in the denser medium. He also interpreted the refractive index as a ratio of velocities in the two media; but, unlike Huygens, assigned the larger speed to the medium of higher refractive index.[2] It was nearly two centuries later that Foucault[3] actually measured the speed of light in media other than air and thus offered experimental proof that the views of Fermat and Huygens were correct.

The electromagnetic theory of Maxwell, enunciated in 1864, substituted electromagnetic waves for elastic waves in the ether which had been assumed by Huygens, but in other respects he did not change Huygens' interpretation. The introduction of the quantum theory during the first quarter of the twentieth century has left the nature of light more of a mystery than ever, and has not as yet furnished any physical meaning for refractive index which is different from or superior to that of Huygens.

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[2] *Principia*, Book I, Proposition 95, Theorem 49.

[3] *Comptes Rendus*, November 24, 1862.

A REMARKABLE HALF-CENTURY

We leave the consideration of Descartes' work in physics by remarking parenthetically that his *Dioptrique* together with his *Discours de la Méthode* and his *Géométrie*, all published together in 1637, mark the beginning of what is possibly the most brilliant half century in the entire history of science, closing as it does with the appearance of Newton's *Principia* in 1687. The invention of analytical geometry was in itself a mathematical revolution, not to mention the calculus of Newton and Leibnitz. The year following saw the introduction of dynamics as one of Galileo's *Two New Sciences*, 1638. The invention of the micrometer by Gascoigne in 1640 and the discovery of the finite speed of light by Römer (1675) set a new pace in astronomical measurements. Von Guericke's air pump, Torricelli's barometer and Pascal's experiments (1648) created the modern theory of fluids, the special case of gases being quantitatively described by Boyle in 1660. The corresponding theorem for the elasticity of solids was enunciated by Hooke in 1676. In the domain of optics, this same half century includes the discovery of diffraction by Grimaldi (1660) and of the true nature of dispersion by Newton; to these must be added double refraction (1669) and the colors of thin plates where the idea of periodicity first makes its appearance in optics. Huygens' explanation of centripetal force and his theory of the physical pendulum (which included the idea of moment of inertia) culminated in the *Principia* which brought to a close this astounding half century. To this period belongs also the establishment of the Royal Society of London and of the Académie des Sciences of France. The reader who cares to look further into the matter will find many noteworthy achievements not mentioned in this brief paragraph, for such men as Mersenne, Gassendi, Roberval and Cavalieri also belong here; but sufficient names have already been given to characterize this intellectual revolution to which there is nothing comparable in the history of science, unless it be the first quarter of the twentieth century and here we are too near the canvas to get a fair perspective.

When we return from this digression to the developmental history of optics, it will be observed that previously to the seventeenth century almost no serious study had been given to questions of color. To the ancients color was a property of the body which exhibited color. The redness of red glass was to them a property, not of the incident light, but of that kind of glass. The rainbow had, of course, been demanding solution from the very dawn of civilization and it was suggested as early as the fourteenth century that this exquisite phenomenon was caused by refraction; while de Dominis (1566–1624) goes more into detail and suggests that the sunlight undergoes two refractions and one reflection at the raindrop.

Descartes in his *Les Météores*, VIII (1637), succeeded in computing from Snell's law the angle which the bow should subtend at the eye of the observer, but he was quite unable to explain the spectral colors. This was first done by Newton who had obtained the key through his study of the composition of white light.

NEWTON'S EXPLANATION OF COLOR

The classical experiments by which Newton established the fact that there is a one-to-one correspondence between the various colors found in sunlight and the various refrangibilities of sunlight are most easily read in his *Opticks*.[4] The essential feature of each of these experiments is the separation of the colors by use of a prism, followed by the isolation of rays of a single color, and then the examination of these isolated homogeneous rays by means of a second prism. In no case, did he find the color of homogeneous light changed by refraction. This was Newton's *experimentum crucis;* but the matter was clinched by still other experiments[5] in which he reproduced white light by compounding the various colors into which he had previously analyzed it. Hence the following conclusions which he printed in the *Philosophical Transactions* for 1672:

> "1. As the Rays of light differ in degrees of Refrangibility, so they also differ in their disposition to exhibit this or that particular colour. Colours are not *Qualifications of Light*, derived from Refractions, or Reflections of natural Bodies (as 'tis generally believed), but *original and connate properties*, which in divers Rays are divers. Some Rays are disposed to exhibit a red colour and no other; some a

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[4] Book I, Part 1, Experiments 12, 13 and 14.

[5] *Opticks*, Book I, Part 2, Experiment 9.

yellow and no other, some a green and no other, and so of the rest. Nor are there only Rays proper and particular to the more eminent colours, but even to all their intermediate gradations.

"2. To the same degree of Refrangibility ever belongs the same colour, and to the same colour ever belongs the same degree of Refrangibility. The *least Refrangible* Rays are all disposed to exhibit a *Red* colour, and contrarily those Rays, which are disposed to exhibit a *Red* colour, are all the least Refrangible: So the *most refrangible* Rays are all disposed to exhibit a deep *Violet Colour*, and contrarily those which are apt to exhibit such a violet color are all the most Refrangible.

"And so to all the intermediate colours in a continued series belong intermediate degrees of refrangibility. And this Analogy 'twixt colours, and refrangibility is very precise and strict; the Rays always either exactly agreeing in both, or proportionally disagreeing in both.

"3. The species of colour, and degree of Refrangibility proper to any particular sort of Rays, is not mutable by Refraction, nor by Reflection from natural bodies, nor by any other cause, that I could yet observe. When any one sort of Rays hath been well parted from those of other kinds, it hath afterwards obstinately retained its colour, notwithstanding my utmost endeavours to change it. I have refracted it with Prismes, and reflected it with Bodies, which in Day-light were of other colours; I have intercepted it with the coloured film of Air interceding two compressed plates of glass, transmitted it through coloured Mediums, and through Mediums irradiated with other sorts of Rays, and diversely terminated it; and yet could never produce any new colour out of it. It would by contracting or dilating become more brisk, or faint, and by the loss of many Rays, in some cases very obscure and dark; but I could never see it changed *in specie*."[6]

THE THEORY OF THE LENS

No longer did anyone believe that color is manufactured by the prism. Each color has its own refractive index and the way was now clear for a complete theory of a single lens. As early as 1647, B. Cavalieri (1598–1647) a Jesuit professor of mathematics at Bologna and a former student of Galileo, first succeeded in obtaining the following expression for the focal length of a lens having faces with different curvatures.

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[6] *Encyclopaedia Britannica*, "Newton."

$$f = \frac{2\, r_1 r_2}{r_1 + r_2}$$

Here it will be observed that the thickness of the lens has been neglected and the refractive index assumed to be the same for different sources of light, namely, 1.50 Our modern expression[7] for the focal length of a single lens, taking account of both thickness and variable refraction, was first derived by Edmund Halley (1656–1742) and published in the *Philosophical Transactions* for November, 1693. Halley will always be held in grateful memory as the man whose mind was sufficiently penetrating to appreciate the importance of Newton's *Principia* and sufficiently generous to see it through the press.[8]

COLOR VISION

At first glance one might think that Newton's long series of cogent experiments dealing with the composition of white light and the mixture of colors had left the science of chromatics and the prismatic analysis of light in a fairly complete state. The facts are quite otherwise. A lapse of more than a century, following Newton's experiments, was needed to discover that, while sunlight contains an infinite number of different kinds (colors) of rays, each distinguished from the others by physical properties (wavelength, etc.) of its own, there are only a very few kinds of sensations which can be produced by sunlight, or light from any white source. This important distinction between the physical and the physiological properties of light was first made clear by Dr. Thomas Young,[9] who showed that light can produce, in the eye, only three fundamental sensations, namely, red, green, and violet. He points out, for example, that the sensation of yellow arises merely from the simultaneous sensations of red and green; that of blue from the addition of green and violet; and so on through all the various shades of the spectrum. If, on the contrary, one attempts to analyze the yellow of a sodium flame into red and green by means of a prism, he fails; nor can the blue light of hydrogen be decomposed into green and violet. In the former case, one is dealing with the physiological properties of the light; in the latter, with the physical properties. This clear distinction of Young's marked a long stride in the history of optics.

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[7] Equivalent focal length $= \frac{1}{\mu - 1}\left[\frac{r_1 r_2}{r_1 + r_2 - \frac{\mu - 1}{\mu} d}\right]$ Lawrence, *General and Practical Optics*, p. 165, London, 1920.

[8] For the whole story, see Brewster's *Life of Newton*, vol. 1, p. 299, et seq.

A second distinction which came rather late is that between spectral colors and the colors of pigments. Newton's experiments on color were bitterly attacked, during many years, by men who relied upon the experience of artists that the three fundamental colors are red, yellow, and blue, and who forgot that the materials of which pigments are made are not, in general, transparent and that, therefore, pigments cannot be added according to the rules for compounding spectral colors.

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[9] *Philosophical Transactions*, 1802; and *Lectures on Natural Philosophy*, xxxvii, p. 439, London, 1807.

DISPERSION AND DEVIATION

Newton's observations have been confirmed with wonderful completeness. Nevertheless, in one instance, he appears to have drawn a hasty conclusion, namely, from the substances which he studied he inferred that the *dispersion* of a prism is always proportional to the *deviation* which it produces. He noted the fact that a glass lens has a different focal length for each color; and, thinking that if he corrected this dispersion by using a second lens of another glass he would at the same time lose the deviation of the rays, he gave up the idea, and bent his energy to the manufacture of a good reflector. Newton's reasons for thinking the case of the refractor desperate will be found in his *Opticks* (third edition, pp. 89–91). It was more than half a century later that C. M. Hall in 1733 and John Dolland in 1758 succeeded in combining crown and flint lenses into an achromatic combination. The man, however, who first made an accurate study of dispersion and refraction, and thus put the subject of achromatism upon a solid foundation was a young German optician who began life as an apprentice boy and died at the age of thirty-nine, Joseph von Fraunhofer (1787–1826). When only twelve years old, Fraunhofer began a six-year apprenticeship in the shop of a mirror-maker and glass-polisher in Munich. At the age of twenty-one, he was a member of an important firm of opticians; and at the age of thirty, he read before the Bavarian Academy of Science an account of his discovery of certain dark lines distributed through the solar spectrum; a discovery which enabled him, for the first time, to identify color accurately and hence to measure refractive indices with a precision hitherto undreamed of. In this epoch-marking paper[10] Fraunhofer gives not only a map of the solar spectrum showing several hundred of these dark lines, but also the refractive indices of many substances for seven different colors, each to the sixth decimal place. Here too is found his discussion of the general principles of the achromatism of the telescope in which the impossibility of perfect achromatism is pointed out and also the necessity of taking into account the luminosity of the various colors which are to be balanced against each other. His observations enable one to write immediately the dispersive power, $\frac{\mu_F - \mu_C}{\mu_D - 1}$ for any of the various substances on his list. That Fraunhofer was master of the practice as well as the theory of lens making is shown by the $9\frac{1}{2}$-inch refractor which he made for the elder Struve then at Dorpat Observatory. The partnership between Guinand, an extraordinarily resourceful Swiss glassmaker, and Fraunhofer, formed in 1805, is responsible for the first "optical glass" worthy of the name and marks the beginning of this industry in which Germany has so long been a leader.

The English chemist, William H. Wollaston (1766–

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[10] *Denkschriften Akad. d. Wiss. zu München,* Bd V, pp. 193–226, 1817.

1828), had observed the dark lines in the solar spectrum as early as 1802: but he never pushed the matter. The only wonder is that these dark solar lines—now known as "Fraunhofer lines"—ever escaped the acute vision and alert mind of Newton; for they are easily seen by viewing, through a 60 degree prism, a narrow strip—say, $\frac{1}{16}$ inch wide—of white paper laid upon a piece of black velvet in the sunshine. Here one is confronted with that very difficult question—impossible of solution—namely, the distribution of merit between two men one of whom has begun some piece of work and the other of whom has completed it. In any event, the joint labors of Newton, Wollaston, and Fraunhofer had laid the foundations of the modern science of spectrum analysis and astrophysics.

THE RISE OF THE WAVE THEORY OF LIGHT

From what precedes it will be clear that the general principles which control the phenomena of reflection, refraction, dispersion, and color were fairly well established without much consideration of what, for want of a better name, may be called the nature of light. This slow progress in reaching the true inwardness of light will not be wondered at by any one who has ever turned over in his mind the subtlety and complexity of a ray of sunlight, or by any one who has pictured himself as equipped with no optical information beyond that of Newton's time. The greatest impasse in modern physics is perhaps that which separates the wave theory and the quantum theory of light; nevertheless the wave theory is so very competent in the laboratory, in the optical factory, in conversation and in thought, that there is little likelihood of its abandonment for many years to come: more probably it will become a large part of a more inclusive theory. Accordingly we proceed to a brief review of its developmental history.

Grimaldi

The first step in any wave theory is the discovery of some periodic phenomenon upon which to base it. In the case of light, this phenomenon appears first to have been described by F. M. Grimaldi (1618–1663) a professor of mathematics in the Jesuit College at Bologna and one of the most acute observers among the many Jesuit fathers who at this period were active in physics: for he is without question the first who saw and recorded the series of bright and dark bands which bound the shadow of any straight edge when illuminated by a point source of light. In his posthumous volume, *Physico-Mathesis de lumine coloribus et iride* (Bononiae, 1665) he gives to this periodic phenomenon the name *diffraction.* The effect is easily seen when one examines the shadow of a knife blade or a lead pencil cast by a naked electric arc some fifty feet or more away. Grimaldi's book contains much speculation, but nothing which need here detain us.

Hooke

The next serious student of the nature of light is Robert Hooke (1635–1703), that brilliant but unfortunate genius who for more than forty years was curator of experiments for the Royal Society of London. He not only observed the diffraction of light independently of Grimaldi, but also studied such sources of periodic phenomena as "blow over" glass, oil on water, soap bubbles—phenomena now grouped under the head of "interference." Unfortunately, however, none of Hooke's optical work is quantitative. Two or three paragraphs from his earlier work[11] will give however a fair picture of the best views concerning the nature of light at the time when Newton was just beginning to think on the problem—the time of Milton, Cromwell, and Charles II:

> "It would be too long, I say, here to insert the discursive progress by which I inquir'd after the proprieties of the motion of Light, and therefore I shall only add the result.
>
> "And, First, I found it ought to be exceeding *quick*, such as those motions of *fermentation* and *putrefaction*, whereby, certainly, the parts are exceeding nimbly and violently mov'd; and that, because we find those motions are able more minutely to shatter and divide the body, then the most violent heats or *menstruums* we yet know. And that fire is nothing else but such a *dissolution* of the Burning body, made by the most *universal menstruum* of all *sulphureous bodies*, namely the Air, we shall in an other place of this Tractate endeavour to make probable. And that, in all extremely hot shining bodies, there is a very quick motion that causes Light, as well as a more robust that causes Heat, may be argued from the celerity wherewith the bodyes are dissolv'd.
>
> "Next, it must be a *Vibrative motion*. And for this the newly mention'd *Diamond* affords us a good argument; since if the motion of the parts did not return, the Diamond must after many rubbings decay and be wasted; but we have no reason to suspect the latter, especially if we consider the exceeding difficulty that is found in cutting or wearing away a Diamond. And a Circular motion of the parts is much more improbable, since, if that were granted, and they be suppos'd irregular and Angular parts, I see not how the parts of the Diamond should hold so firmly together, or remain in the same

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[11] *Micrographia*, London, 1665.

sensible dimensions which yet they do. Next, if they be *Globular*, and mov'd only with a *turbinated* motion, I know not any cause that can impress that motion upon the *pellucid medium*, which yet is done. Thirdly, any other *irregular* motion of the parts one amongst another, must necessarily make the body of a fluid consistence, from which it is far enough. It must therefore be a *Vibrating* motion.

"And Thirdly, That is a very *short vibrating motion*, I think the instances drawn from the shining of Diamonds will also make probable. For a Diamond being the hardest body we yet know in the World, and consequently the least apt to yield or bend, must consequently also have its vibrations exceeding short.

"And these, I think, are the three principal proprieties of a motion, requisite to produce the effect call'd Light in the Object" (pp. 54–56).

These suggestive guesses of Hooke, published in the same year with Grimaldi's book, lead up to the quantitative work of Newton, who made careful measurements of the phenomena of diffraction as seen when a beam of light passes between two knife edges and also of the periodic phenomena seen when light is transmitted or reflected through thin plates.

Newton

In the case of a man so thoroughly saturated with the idea of gravitation and so firmly convinced that light consists of small particles of matter in motion, as was Newton, it is not surprising to find him explaining the diffraction of light in terms of a sort of periodic attraction by the ordinary matter of the straight edge for the light-corpuscle which is passing near it. Current views concerning diffraction (or *inflexion*, as Newton called it) at the close of the seventeenth century are perhaps fairly set forth in the following queries which Newton places at the end of his discussion:

> "Query 1. Do not Bodies act upon Light at a distance, and by their action bend its Rays; and is not this action (*caeteris paribus*) strongest at the least distance?
>
> "Qu. 2. Do not the Rays which differ in Refrangibility differ also in Flexibility; and are they not by their different inflexions separated from one another, so as after separation to make the Colours in the three Fringes above described? And after what manner are they inflected to make those Fringes?
>
> "Qu. 3. Are not the Rays of Light in passing by the edges and sides of Bodies, bent several times backwards and forwards, with a motion like that of an Eel? And do not the three Fringes of colour'd Light above-mention'd arise from three such bendings?
>
> "Qu. 4. Do not the Rays of Light which fall upon Bodies, and are reflected or refracted, begin to bend before they arrive at the Bodies; and are they not reflected, refracted, and inflected, by one and the same Principle, acting variously in various Circumstances?
>
> "Qu. 5. Do not Bodies and Light act mutually upon one another; that is to say, Bodies upon Light in emitting, reflecting, refracting and inflecting it, and Light upon Bodies for heating them, and putting their parts into a vibrating motion wherein heat consists?"[12]

In his explanation of the colors of thin plates Newton was much happier; for here, while still employing the corpuscular theory, he makes a highly accurate set of measures which, with a few verbal changes, are at once interpretable into recent optics. Having placed a lens whose radius of curvature was 91 inches upon a flat plate of glass, he measured the diameters of the various rings produced in the thin layer of air between the two glasses; and arrived at the conclusion that "the thickness of the air at the first of these dark rings" is 1/88739 part of an inch. Now this distance is interpreted by Newton to mean just half the distance between two successive fits of easy (or difficult) transmission of the corpuscles; or, as we say today, it is half a wave length of light. The modern value for half a wave length of yellow light is 1/85100 part of an inch. The diameters of the bright rings Newton found to be proportional to the series of odd numbers, 1, 3, 5, 7, etc., and those of the dark rings to be proportional to the even numbers, 2, 4, 6, 8, etc. By these careful experiments which Newton describes in the second book of his *Opticks* and which must ever remain a pattern for an investigator in a new field, is established beyond doubt the periodicity which is inherent in every ray of light.

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[12] *Opticks*, fourth edition, pp. 313–314.

Huygens

Simultaneously with Newton another great mind, Christiaan Huygens, whose acquaintance we have already made, was at work on the nature of light along a quite different line.

Huygens, who was living in Paris at the time when Römer discovered the finite speed of light, 1675, shortly afterwards read a paper before the French Academy in which he showed how this finite speed, as well as the phenomenon of reflection and refraction, might be most simply explained. This paper was printed in 1690 some twelve years after its reading, under the title *Traité de la lumière* (Leyden, 1690). The author begins by assuming a luminiferous ether which indeed had already been supplied by Descartes and others. Then each luminous particle is taken to be a source of pulses or waves which it communicates to the surrounding ether in somewhat the same way in which one billiard ball transmits an impulse to another.

Upon these relatively simple hypotheses, Huygens erected a principle from which all the experimental results of his time flow as eminently natural consequences. This principle is phrased by Fresnel, its most brilliant user, as follows:

> "The vibrations at each point in the wave-front may be considered as the sum of the elementary motions which at any one instant are sent to that point from all parts of this same wave in any one of its previous positions, each of these parts acting independently the one of the other."

The elegant manner in which Snell's Law is derived and the "strange refraction of Iceland crystal" accounted for, may be followed by the English reader in Silvanus P. Thompson's translation of Huygens' *Treatise on Light* (Macmillan, London, 1912). The idea of a wave front as the envelope of a certain set of secondary waves and the idea of light in isotropic media proceeding along the normal to the wavefront having once been made clear, one might well think that the explanation of optical phenomena in terms of the wave theory would rapidly become fashionable; but the facts are quite different. For more than a century after the death of Huygens his views met small acceptance. The reason for this hysteresis between the enunciation and the adoption of the wave theory lies partly in the fact that the waves of Huygens were rather pulses than trains of waves, partly in the fact that the phenomenon of interference had not yet been clearly set forth and in some extent, though perhaps less than is generally believed, to the overpowering authority of Newton. Then, too, men were daily acquiring an increased respect for the experimental method and an increased distrust of any principle arrived at as a mere consequence of certain hypotheses.

Young

At the outset of the nineteenth century, a remarkable young English physician contributed a new experimental fact and a new idea to the discussion as to the nature of light. Everyone understands that when an extra candle is lighted in a room the illumination of the room is invariably increased; everyone knows that the raising of a blind at the window adds to the illumination of the room: but this youthful doctor, Thomas Young (1773–1829) devised an experiment to show that two lights may be added together so as to produce an illumination which is not more, but much less than either one alone. The two sources of light he obtained by making two pinholes or cutting two parallel slits very close together, say 0.5 millimeter apart, in an opaque screen, such as a visiting card, and then viewing through this any small and comparatively distant source of light. When such a screen is held close to the eye, the observer always sees a set of bright and dark parallel bands. Either pinhole alone gives a continuous bright field: but when the field is illuminated by both there are certain regions, dark bands, where the illumination produced by one pinhole is completely annulled by that from the other.[13] Just how

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[13] For Young's own account of this experiment see his *Lectures on Natural Philosophy*, vol. I, p. 464, London, 1807.

Young was led to this experiment and the fertile idea of interference is told in his own words as follows:

> "It was in May, 1801, that I discovered, by reflecting on the beautiful experiments of Newton, a law which appears to me to account for a greater variety of interesting phenomena than any other optical principle that has yet been made known. I shall endeavour to explain this law by a comparison.
>
> "Suppose a number of equal waves of water to move upon the surface of a stagnant lake, with a certain constant velocity, and to enter a narrow channel leading out of the lake. Suppose then another similar cause to have excited another equal series of waves, which arrive at the same channel, with the same velocity, and at the same time with the first. Neither series of waves will destroy the other, but their effects will be combined: if they enter the channel in such a manner that the elevations of one series coincide with those of the other, they must together produce a series of greater joint elevations; but if the elevations of one series are so situated as to correspond to the depressions of the other, they must exactly fill up those depressions, and the surface of the water must remain smooth; at least I can discover no alternative, either from theory or from experiment.
>
> "Now I maintain that similar effects take place whenever two portions of light are thus mixed; and this I call the general law of the interference of light."[14]

Here was an idea which immensely extended the possibilities of the wave theory set forth by Huygens; for Young's principle of interference made it at once possible to explain the colors of thin plates and diffraction past a straight edge, in addition to refraction and reflection, in terms of waves. Young thus embraced in his wave theory a much larger group of phenomena than either Newton or Huygens had been able to do. Nevertheless it was shortly discovered that Young's explanation of some fundamental phenomena, such as diffraction through a single narrow slit, where he considers the two edges of the slit as secondary sources of light which interfere in the shadow on either side of the slit, were not valid; for predictions made upon this basis did not agree with the observed distances of the diffraction bands. In spite of this defect in Young's theory it was his achievement to establish incontestably the great and simple principle of interference, which at once immensely extended the reach of the wave theory of light.

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[14] *Works*, I, pp. 202–203.

Fresnel

At this point a brilliant young French engineer, Augustin Fresnel (1788–1827), became interested in optical problems and within the eleven years between 1815 and 1826 carried out a series of cleverly designed experiments, and erected upon them as a foundation what is practically our present undulatory theory of light.

COMBINATION OF HUYGENS' PRINCIPLE AND THE PRINCIPLE OF INTERFERENCE

If Fresnel's contributions were to be summarized in a single sentence, one might say that he united Young's principle of interference with the principle of Huygens; so that the interfering sources of light, in any case of diffraction, became, not the edges of the diffracting screen, but the various half-wave-length zones into which the wavefront may be divided with reference to any particular point at which the illumination is desired

Young's idea that the diffraction fringes produced by a single narrow slit arise from the interference of rays reflected from the two edges of the slit, was quickly disproved by Fresnel as follows: two razors were placed with their edges parallel and facing each other so as to form a narrow slit, and the diffraction phenomena observed. Next, the *backs* of the razors were placed so as to face each other; and it was found that, for the same width of slit, the diffraction phenomena in the two cases were identical, in spite of the fact that in one case the edges were excellent reflectors and in the other case had practically no reflecting surface.

Armed with this powerful combination of the ideas of Huygens and Young, Fresnel proceeded to show how practically any case of diffraction may be solved by adding up (integrating) the effects produced by all the elements of the incident wave surface. A large number of interesting special cases of this kind were solved by F. M. Schwerd in his volume entitled *Die Beugungserscheinungen aus d. Fundamentalgesetzen d. Undulationstheorie analytisch entwickelt* (Mannheim, 1835). This general solution of the diffraction problem is the first of three great steps which we owe to Fresnel.

THE INTERFERENCE OF POLARIZED LIGHT

His second step was the discovery of the conditions under which polarized light can interfere, a discovery which suggested to him the transversality of light waves. These conditions were found to be as follows:

> "(1) Two rays of light *polarized at right angles* do not produce any effect upon each other under the same circumstances in which two rays of ordinary light produce destructive interference.

"(2) Rays of light polarized in the same plane interfere like rays of ordinary light; so that in these two kinds of light the phenomena of interference are absolutely identical.

"(3) Two rays which were *originally polarized at right angles* may be brought to the same plane of polarization *without thereby acquiring the ability to interfere.*

"(4) Two rays of light polarized at right angles and afterwards brought into the same plane of polarization interfere like ordinary light, provided they were originally polarized in the same plane."[15]

In the history of optics, the first of these experimental conditions is an all-important one, since it suggested to and convinced Fresnel that light waves are transversal, and not longitudinal as he and Young had hitherto thought. A new and satisfactory picture of a polarized ray was thus obtained for the first time. The "sides" which Newton[16] attributed to rays had now acquired a physical meaning, namely, the plane of vibration.

This idea of transversal vibrations met with slow acceptance. Hitherto the ether had been thought of as a fluid substance. Men of the type of Laplace, Poisson, Biot, and even Arago were utterly opposed to admitting the possibility of transverse vibrations in a fluid. To these objections, Fresnel replied that the ether behaves as an elastic solid. Indeed, it was not until five or ten years after Fresnel's death (1827) that the emission theory of Newton could be said to have been given up.

The third of Fresnel's memorable discoveries came during a search after the effect which the crystalline medium produces upon a ray of light that penetrates it.

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[15] *Ann. de chimie et de Physique*, t. x, p. 288, 1819.

[16] *Opticks*, Book III, Query 26.

Erasmus Bartholinus, the Dane, had already (1669) observed that Snell's law must be modified in the case of a ray passing into Iceland spar, since the ordinary law of refraction contemplates but a single ray, while this spar gives rise to *two* refracted rays. The new law, i.e., the appropriate idea, was found by Huygens who described the path of the ordinary and extraordinary ray in any uniaxial crystal by drawing two concentric wave surfaces, one an ellipsoid of rotation, the other a sphere whose radius is equal to the minor axis of the ellipsoid. The essence of the matter is contained in the following sentence:

> "I will add here, before passing away, that in comparing together the regular and irregular refraction of this crystal, there is this remarkable fact, that if ABPS be the spheroid by which light spreads in the Crystal in a certain space of time (which spreading, as has been said, serves for the irregular refraction), then the inscribed sphere BVST is the extension in the same space of time of the light which serves for the regular refraction."[17]

This extension of Snell's law to cover double refraction proved to be insufficient, however, to include a phenomenon discovered by Fresnel in a crystal of topaz; for in this particular substance, as in all biaxial crystals, neither of the two refracted rays has a constant index of refraction; both of them are "extraordinary." Fresnel's power of invention appears to have been almost unlimited; for he succeeded in replacing the wave surface of Huygens by one of the fourth degree which describes with remarkable accuracy the behavior of both uniaxial and biaxial crystals; and has even shown itself capable of predicting a new phenomenon, conical refraction.

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[17] *Traité de la lumière,* chapter v, paragraph 33.

The fourth degree equation of Fresnel's wave surface was derived by connecting the speed of light in the medium with the elastic properties of the medium, and by remembering that the desired surface (whatever its equation) degenerates, in special cases, into two second degree surfaces. It is this feat of accurate mathematical description which we shall call the third remarkable achievement of Fresnel, and which, together with the two above mentioned, gives him an undisputed place as the creator of the wave theory of light.

The manner in which artrophysicists and spectroscopists have employed this wave theory will be considered in a later chapter.

The circumstances under which Fresnel worked demand a moment's consideration. He was born at Broglie in Normandy in 1788: entered the great military school of France, the Ecole Polytechnique, at the age of sixteen and went immediately into the department of Ponts et Chaussées; spent the next nine years in routine work on the highways in various parts of France; then lost his appointment, on the return of Napoleon from Elba, because of sympathy expressed for the Bourbons. After Waterloo, however, he obtained a post as engineer in Paris and here took up the serious study of optics with the brilliant consequences detailed above. On July 14, 1827, he died of tuberculosis, against which he had set up a brave fight for many years.

Dr. Thomas Young was a somewhat older man than Fresnel. An English Quaker by birth and training, he went to Edinburgh in 1794, took his degree in medicine at Göttingen in 1796, returned to England and entered

Emmanuel College at Cambridge in 1797. He soon became one of the most variously educated men the world has ever seen. An accomplished linguist, skilled in music and athletics, he completed his medical studies at Cambridge in 1800 and at once settled as a practicing physician in London. In the year following he was appointed to the professorship of natural philosophy in the then newly founded Royal Institution, a position which he resigned at the end of two years. It was during this period that he wrote his celebrated *Lectures on Natural Philosophy* and published his three most important papers on optics. His activity outside of physics was tremendous, such as is possible only to a very select few.

CHAPTER VII

THE PIONEERS IN ELECTRICITY AND MAGNETISM

"Here about the beach I wandered
Nourishing a youth sublime
With the fairy tales of Science
And the long results of time."
—TENNYSON, *Locksley Hall*, VI.

We come now to a field of physics which was practically unknown and uncultivated by the ancients. They were of course familiar with the curious properties of a fossil resin which the Greeks called "electron" and which we call "amber;" they knew also that native lodestone would attract iron; they were familiar with the disastrous effects of lightning and with the sting of the electric eel; but none of these facts did they associate with the amber phenomenon. The result is that the history of electricity begins practically with the work of Dr. Gilbert published in 1600 and the story of magnetism with the *Epistola* of Petrus Peregrinus written in 1269.

The history of the mariner's compass is shrouded in mystery: the earliest references to it in the literature of western Europe probably date from the year 1190. Peregrinus made a careful experimental study of magnetism, used a spherical magnet, showed how to locate the two points at which the magnetic meridians of the sphere meet, and proposed the names, north and south poles, for these points. The following sentence from

Chapter VIII of the *Epistola* would seem to indicate that Peregrinus was familiar with the fact that magnetization may be destroyed by mechanical jarring and also that he was acquainted with the process of magnetization by induction.

> "If, however, violence is used towards the ends, so that, for instance, the Southern end of the iron which was touched with Northern end of the magnet is now touched with the Southern end of the magnet * * * the power in the iron will easily be changed, and that will become Southern which was previously Northern, and the converse."

The centuries which precede Peregrinus contain many references to the magnet but most of them are old wives' tales or idle dreams. Many stories of this type are related in the earlier pages of Mottelay's *Bibliographical History of Electricity and Magnetism* (London, 1922). If one's object be to discover the belief of the common people at any particular period, there is no better method than to follow through all these mistaken notions. Since, however, our purpose is merely to trace the succession of the essential ideas and facts which now constitute the science, we pass at once to the work of Dr. William Gilbert (1540–1603) an Englishman who studied medicine at Cambridge, practiced it in London, became physician to Queen Elizabeth, and also the leading man of science in the England of his day.

THE MAGNETISM OF THE EARTH

Gilbert's great work is his *De Magnete* (London, 1600), which is a compendium of the magnetic knowledge of that period, set forth in the systematic form of a treatise.

In addition to the general properties of a magnet, one finds here a complete discussion of the magnetic dip, discovered in 1544, by George Hartmann, a German priest, but first announced in 1576, by Robert Norman, English compass-maker: also of the magnetic variation well known to navigators since 1436, when the Italian, Andrea Bianco, published his charts. Gilbert's statement that the variation is constant with respect to time was shortly disproved as one after another, the secular, annual, and diurnal variations were discovered. The most important contribution of Gilbert is almost certainly the idea that the earth itself is a great magnet: for this brings at once all the phenomena of terrestrial magnetism —still an outstanding unsolved problem of present day physics—into the same category with the compass needle and the ordinary magnet of the laboratory. Book VI of the *De Magnete* is devoted to this subject. In Book V he points out the very significant fact that the earth exerts a couple, but not a force, upon a compass needle, a fact earlier published by Robert Norman. In Book II is introduced the field of force in a qualitative way—an *orbis virtutis*, surrounding each magnet—the idea which Faraday afterward employed so powerfully.

It is nearly two centuries later (1776) that the first quantitative measures of the field of magnetic force about the earth were made by Borda (1733–1799), the French astronomer and navigator. Comparative intensities were obtained by measuring the vibration periods of a vertical needle placed in the magnetic meridian. This completes the introduction of the three elements of the terrestrial field—*variation*, *dip*, and *intensity;* but leaves us still far removed from the day when these results can be expressed in absolute—and therefore easily comparable—units.

MAGNETISM A MOLECULAR PHENOMENON

The demagnetization of iron by bringing it to a red heat was clearly known to Gilbert and it is highly probable that he inferred from this fact that magnetization is a molecular phenomenon. Witness the following

> "When a piece of iron has been touched by a lodestone, if it be placed in a hot fire until it is perfectly red hot and remain in the fire some considerable time, it will lose that magnetick strength it had acquired. Even a lodestone itself through a longish stay in the fire, loses the powers of attracting implanted and innate in it, and any other magnetick powers."[1]

The idea that magnetism is a molecular phenomenon found complete verification in the mathematical treatment given to the subject by Poisson (1781–1840) on the basis that any magnet is built up of small "magnetic elements" or molecules, in which the north and south magnetic "fluids" are displaced to the ends of the molecules as soon as the iron is brought into a magnetic field. In this way Poisson accounted for the forces of attraction and repulsion, as shown by experiment between magnets of various shapes placed in various positions. What would be a final proof of the molecular nature of magnetism,—if ever anything were final in physics—was given by Sir James Ewing,[2] who designed a model magnet built up of tiny compass needles, each mounted on a pivot, and the whole combination showing the phenomena of magnetic induction and hysteresis in a very perfect manner. It is almost unnecessary to add that since 1890 new and more complicated models have been devised to explain new and more complicated magnetic phenomena.

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[1] *De Magnete*, p. 66.

[2] *Philosophical Magazine*, September, 1890.

THE LAW OF INVERSE SQUARES ESTABLISHED BY COULOMB, GAUSS AND WEBER

The next great step in magnetic science was the experimental demonstration by C. A. Coulomb (1736–1806) of the fact that magnet poles attract or repel each other with forces which vary inversely as the square of the distances separating them.

These results were obtained in 1784 by means of the torsion balance of which Coulomb had made himself a thorough master. They gave to magnetic inquiry a quantitative basis which it had never before possessed, and which at once made itself felt in the work of Poisson mentioned above and in the rapid development of our knowledge of the earth's magnetic field in the hands of Hansteen and Gauss.

Tremendous interest was aroused by Hansteen's *Magnetismus der Erde* which appeared in 1819. Within the twenty years immediately following the publication of this work many magnetic observatories were established in distant parts of the earth, magnetic expeditions were sent to remote latitudes to determine the magnetic elements in various places, and international coöperation became a fact for the first time in the history of science.

C. F. Gauss (1777–1855) the great German astronomer and mathematician, made the next important step when in 1833, in his first memoir on the theory of magnetism, he showed how magnetic measurements—such as that of the moment of a magnet or that of the intensity at any point—, could be made in terms of three fundamental units, such as those of *length*, *mass*, and *time*. In this work he associated with himself the professor of physics at Göttingen, Wilhelm Weber, and between the years 1836 and 1839 they published their *Resultate aus den Beobactungen des Magnetischen Vereins*. Here will be found Gauss's theory of that outstanding mystery of modern physics, terrestrial magnetism. This theory consists in deriving from a limited number of observations on the three elements (intensity, dip, and variation) the values of the coefficients in a series which expresses the value of a certain function, which, once known, yields values of the elements for any point whatever on the earth's surface by the simple process of differentiation; and this without making any assumption as to magnets distributed throughout the interior of the earth.

The introduction of the system of absolute measurements put new life and breath into the whole subject of physics. The union between Gauss and Weber was vastly more important than the Magnetic Union which published their results; for, from this time on, it became easily practicable for different observers to use the same (or comparable) fundamental units and thus render the results obtained by any one man immediately intelligible and available to every other man. Gauss in his great paper of 1833 on the *Absolute Measure of the Earth's Magnetic Force* thus started a universal language of physics analogous to that of mathematics which had long been spoken by all civilized nations.

THE EARLY HISTORY OF ELECTRICITY—GILBERT AND VON GUERICKE

Up to the year 1820—the year of Oersted's great discovery—the histories of magnetism and electricity are quite independent. Nevertheless it curiously happened that the first important treatise on the subject of electricity is the great second chapter of the second book of Dr. Gilbert's *De Magnete.* Prior to the beginning of the seventeenth century, the strange properties of rubbed amber and of the magnet were mainly playthings in the hands of the unscrupulous.

> "Inquisitive theologians also would throw light on the divine mysteries set beyond the range of human sense, by means of lodestone and amber; just as idle Metaphysicians, when they are setting up and teaching useless phantasms have recourse to the lodestone as if it were a Delphick sword, an illustration always applicable to everything." * * * "So in very many cases there are some who when they are pleading a cause and cannot give a reason for it, bring in lodestone and amber as though they were personified witnesses."[3]

In sharp contrast with this kind of talk, reminding one of what we hear in the present time concerning telepathy and clairvoyance, Gilbert proceeded to collect from his own observations a great body of experimental fact concerning the behavior of electrified bodies. His first step was to devise an electroscope and to discover that the moist air of an English summer seriously interferes with electrostatic experiments.

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[3] Gilbert, *De Magnete*, Book II, chapter 2. For many fake stories of this type see Book II of Sir Thomas Browne's *Vulgar Errors*.

> "Sulphur also attracts, and mastick and hard sealing-wax compounded of lac tinctured of various colours. Rather hard resin entices, as does orpiment, but less strongly; with difficulty also and indistinctly under a suitable dry sky, Rock salt, muscovy stone, and rock alum. This one may see when the air is sharp and clear and rare in midwinter, when the emanations from the earth hinder electricks less and the electrick bodies become more firmly indurated. * * * But in order that you may be able clearly to test how such attraction occurs, and what those materials are which thus entice other bodies (for even if bodies incline towards some of these, yet on account of weakness they seem not be raised by them, but are more easily turned), make yourself a versorium of any metal you like, three or four digits in length, resting rather lightly on its point of support after the manner of a magnetick needle, to one end of which bring up a piece of amber or a smooth and polished gem which has been gently rubbed; for the versorium turns forthwith."[4]

The electroscope here described under the name of *versorium* is precisely that which Tyndall employed in his lectures at the Royal Institution, using for a pivot an egg placed in the top of a glass lamp chimney and for the needle a wooden lath which could be seen from all parts of the house. Never dreaming that electrification could be conducted from one body to another, Gilbert did not, like Tyndall, insulate the needle of his *versorium;* consequently all electrified bodies caused his needle to rotate by attracting the nearer end. He at once observes that:

> "All bodies are drawn to electricks except those which are aglow and aflame, and highly rarefied." * * * A lodestone appeals to magneticks only; towards electricks all things move. * * *

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[4] *De Magnete*, Book II, Chapter 2.

When electricks which have been rubbed are applied quickly to a versorium then especially at once they act on the versorium, and it is attracted more when near them."

The keen observational power of Gilbert is well illustrated in what he says concerning the effect of an electric field upon freshly produced smoke:

"For electrical effluvia have the virtue of and are analogous with extenuated humour; but they will produce their effect, union and continuity, not by the external impulse of vapors, not by heat and the attenuation of heated bodies, but by their humidity itself attenuated into its own peculiar effluvia. Yet they entice smoke sent out by an extinguished light; and the more that smoke is attenuated in seeking the upper regions, the less strongly it is turned aside; for things that are too rarefied are not drawn to them; and at length, when it has now almost vanished, it does not incline towards them at all, which is easily seen against the light."[5]

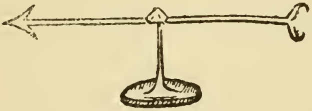

FIG. 7. DR. GILBERT'S VERSORIUM

All this some three centuries before anything was known about the recombination of ions into neutral molecules. Everything electrical is explained in terms of "effluvia." All bodies fall into one or the other of two classes, namely, "electricks," i.e., those bodies which, after being rubbed rotate the versorium, and "non-electricks," i.e., bodies which have no effect upon the versorium. The word

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[5] *De Magnete,* p. 59. Translation by the Gilbert Club.

"electricity" makes its first appearance nearly a half century later. Sir Thomas Browne (1605–1682) deliberately coins it in the following sentence from his *Pseudodoxia Epidemica.*[6]

> "Again the concretion of ice will not endure a dry attrition without liquation; for if it be rubbed long with a cloth, it melteth. But crystal will calefy unto electricity, that is, a power to attract straws or light bodies, and convert the needle freely placed."

The new science of electricity now included a well established body of fact and a limited but helpful nomenclature. The next important step was taken by O. von Guericke (1602–1686) whose name is always to be associated with that of Kepler—these two being the outstanding physicists of Germany during the seventeenth century. What von Guericke did was to devise a machine for producing electric charges, a rotating sphere of sulphur against which the hand of the operator was placed and thus by continuous friction furnished a stream of electricity through the body of the operator. One essential feature of the socalled electrical machine was however still lacking—that is, the *collector* or *prime conductor*, a large insulated metallic body, what we would now call a *condenser*, provided with a comb of sharp points by which the charge opposite in sign to that of the sulphur ball was drawn off, leaving the conductor charged with electrification of the same sign as the sulphur or glass sphere. This collector was added by G. M. Bose of Wittenberg in the year 1744; and thus with the substitution by Winkler of

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[6] *Vulgar Errors*, Book II, Chapter 2, 1646.

Otto von Guericke (1602–1686)
German experimental philosopher

a fixed rubber for the human hand practically brought to completion this form of electrical machine.

Von Guericke's experiments[7] resulted not only in the invention of this machine—a matter of minor importance involving no new principle—but they also brought to light a number of new phenomena, such as the crackling noise, shimmering light, and conduction through a short distance accompanying the operation of the machine.

Von Guericke was a man of excellent university training, and also a man of affairs, busy with diplomatic missions during the dark stormy period of the Thirty-Years War. It is quite remarkable that during the later years of his life he should have found energy and time to carry on electrical researches. His machine and all its variants with glass disks instead of sulphur spheres are now of course entirely superseded by the influence machine.

ELECTRIC CONDUCTION—STEPHEN GRAY

The next important contribution to electrical science comes from a man of whom very little is known, Stephen Gray (1696–1736). His biography does not appear in the *Encyclopaedia Britannica;* but a few words about him will be found in the *Dictionary of National Biography;* and an excellent sketch of his life and work in *Science Progress*, July, 1924, pp. 102–114. He was a pensioner of the Charterhouse and like many another blue coat boy left a name that will not soon be forgotten; for he reported to the Royal Society of London the new fact that:

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[7] *Experimenta Nova,* 1671.

> "The Electrick Vertue of a Glass Tube may be conveyed to any other Bodies so as to give them the same Property of attracting and repelling light Bodies as the Tube does, when excited by rubbing: and that this attractive Vertue might be carried to Bodies that were many Feet distant from the Tube."

Gray's discovery (1729) that electricity can be transported, over metallic wires and wet strings, to bodies seven or eight hundred feet distant, raised a serious difficulty in the minds of those who had hitherto considered electrification to be an effluvium or enveloping atmosphere. The next step—the discovery that this property of handing on the electrical effect is limited to a certain class of substances—was at once taken. This class of bodies, called *conductors*, was identified, by Desaguliers, (1683–1744), with the class to which Gilbert had already given the name of *non-electrics;* and conversely, the *electrics* of Gilbert became the *non-conductors* of Gray.

THE DISCOVERY OF POSITIVE AND NEGATIVE ELECTRIFICATIONS

Building upon the foundations laid by Gilbert and von Guericke, and, inspired by Gray, comes a young Frenchman, C. F. Dufay (1698–1739) belonging to the court circle of Louis XV, with a new and tremendously surprising contribution. At this period it was well known that when a light body such as a bit of eider-down or gold leaf is electrified by contact it is at once repelled by the body which has electrified it. Dufay now put to nature the following question, Is the electrified gold leaf repelled by electrified bodies *other than the one from which it obtained its own electrification?* It was, of course, a matter of experiment. He found that gold leaf electrified from rubbed glass was repelled by rubbed glass; but was attracted by rubbed resin. Dufay puts the matter as follows:

> "Seventhly, chance has thrown in my way another Principle more universal and remarkable than the preceding one and which casts a new Light on the Subject of Electricity. This Principle is that there are two distinct Electricities, very different from one another; one of which I call *vitreous* Electricity, and the other *resinous* Electricity. The first is that of Glass, Rock-Crystal, Precious Stones, Hair of Animals, Wool and many other bodies. The second is that of Amber, Copal, Gum-Lack, Silk, Thread, Paper and a vast Number of other Substances.
>
> "The characteristic of these two Electricities is that a body of *vitreous* Electricity, for example, repels all such as are of the same Electricity; and on the contrary attracts all those of the *resinous* Electricity."[8]

Quite naturally Dufay gave to the two kinds of electricity which he had just discovered (1735) the names *vitreous* and *resinous*, names for which Franklin almost immediately suggested the terms *positive* and *negative*. The first use of Franklin's names in the *Philosophical Transactions*, occurs in volume 45, p. 99 (1748). They have been retained in use during a period of nearly two centuries, not because the positive character of vitreous electricity had been established by any good evidence, but probably on account of the simplicity and naturalness of Franklin's theory of one electric fluid present in normal amount in a neutral body, as compared with two fluids possessing the puzzling property of mutually annihilating each other. Since Sir J. J. Thomson's study of electrons (1897) it has been clear that the names *positive* and *negative* might well be interchanged, were it not for the enormous confusion which would thus be introduced in electrical literature; since Thomson has made it clear that when electricity is removed from a neutral body that body becomes vitreously electrified, i.e., positively electrified in Franklin's sense. It is to Franklin, however, that we owe the important idea that when a body is electrified its equilibrium is disturbed.

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[8] *Philosophical Transactions*, 38, p. 263, 1734.

ELECTROSTATIC INDUCTION; CONDENSER AND ELECTROSCOPE

It is now clear, even to the tyro in electricity, that when rubbed amber attracts a bit of paper it does so in virtue of the electric charge which the amber "induces" on the nearest portion of the paper. This curious attraction was a great puzzle to Thales and to Gilbert, and to all the intervening generations; as indeed it is to us of the present day. Their background however did not include, as ours does, the distinction between conductors and non-conductors; they were not aware of two kinds of electricity; they had no conception of the law of inverse squares; and hence they were greatly concerned as to the explanation of the fundamental fact of electrical attraction. Our knowledge of electrical phenomena has so tremendously increased since the time of Gilbert that we are prone to forget that the basic fact of attraction between positive and negative charges remains totally unexplained. The fundamental phenomenon of *induc-*

tion which underlies the manufacture and use of the electrical condenser appears first to have been seriously studied by Stephen Gray, who showed that electrical effects can be communicated to a line of pack-thread without any contact between the pack-thread and the electrified body. This experiment belongs to the year 1729—two years after the death of Newton. The first striking case of induction, however, came to the notice of a cathedral dean in Germany, von Kleist, in the year 1745; and independently a few months later in the laboratory of Pieter van Musschenbroek at Leyden when Musschenbroek's friend, Cunaeus, happened to grasp with one hand a bottle of water into which dipped a wire from the prime conductor of an electrical machine while, with the other hand, he happened to touch this terminal which was dipping into the water. The result was a severe shock; and ever since this combination of two conductors separated by a non-conductor, one of the conductors being insulated, the other connected to earth, has been known as a Leyden jar, or since the time of Volta (1782) as a *condenser*.

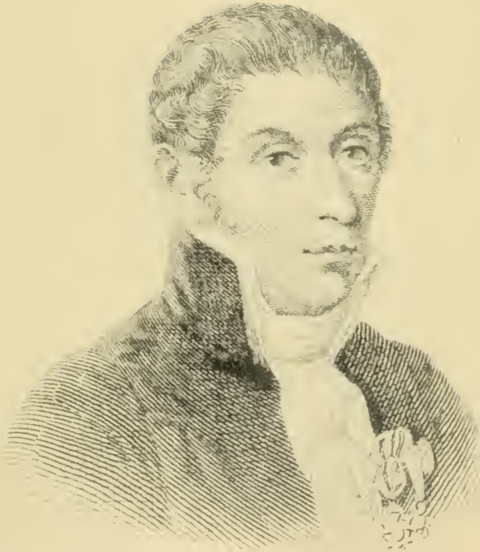
Tin foil was soon substituted for the water inside and also for the hand outside the glass bottle; but the behavior of the Leyden jar was first completely studied and explained by Benjamin Franklin in the years 1747–1748. He showed that a charge given to the inner coating of the jar induces a bound charge *of opposite sign* on the other coating, and at the same time, drives to earth an equal charge of the same sign as that given to the inner coating. He insulated both coatings; he removed them one at a time to show that the essential feature of the jar was the insulating medium, he verified his views by discharging convectively an insulated jar—Franklin's pane and Franklin's chimes; all this without those helpful ideas of potential, capacity and energy which so simplify the matter for us. Not only so but he showed that Leyden jars joined in parallel are merely equivalent to a jar of larger area; while jars joined in series (cascade) have the effect of merely increasing the thickness of the insulating medium. The modern condenser whether using air, oil, glass, or mica as a dielectric is essentially a pile of "Franklin panes." Of all the applications of the principle of electrostatic induction none is more interesting than that found in the gold leaf electroscope which was first made by Abraham Bennett (1750–1799) and described by him in the *Philosophical Transactions*, 1787—shortly after the close of the Revolutionary War. Bennett also invented what he called a revolving doubler which enabled one to start with a very *small* charge and obtain an indefinitely large amount of electricity without the use of friction. The work spent in rotating the disk of this machine, with its induced charge, from a region of low to a region of high electrical pressure accounts for the energy of the charge obtained. The recent improvements introduced by a long series of workers—Belli, Varley, Toepler, Holtz, Voss, Wimshurst, and others lie quite outside the limits of this chapter.

THE TORSION BALANCE AND THE LAW OF INVERSE SQUARES

From what precedes it is evident that ignorance of the law according to which electric force varies with the distance did not prevent the discovery of a great body of important electrical truth. Nevertheless the quantitative description of these phenomena was compelled to await Coulomb's invention of the torsion balance, an instrument which measures very small forces with great accuracy. With this instrument, which dates from 1784 and which has already been mentioned under the head of magnetism, Coulomb measured the electric intensity at the surface of globes, cylinders, and other conductors, under various circumstances. The identity of the law describing electrical attraction and repulsion with that of gravitation at once rendered available many important astronomical results for use in electrostatics and at the same time served as an impetus toward mathematical discovery as can be seen from the papers of Laplace, Poisson, Green and others. Electrostatics was now beyond the pioneer stage; and quite ready for the introduction of the powerful ideas of *potential* and *potential difference.* We may, therefore, perhaps close this chapter on electrical pioneers with a brief account of the facts which led up to the discovery of a method for the production of continuous electric discharges.

THE VOLTAIC CELL

It is a commonplace that a large number of discoveries of the first order have resulted from a casual observation persistently followed up. A case of this kind occurred in the laboratory of Luigi Galvani (1737–1798), an Italian physiologist at Bologna, in the year 1780, when one of his assistants happened to touch the inner crural nerve of a dissected frog with the point of his scalpel and observed that the legs of the frog were violently convulsed. A series of following-up experiments showed that the essential feature of the stimulus to the frog was a chain of two different metals joined at their free ends by the muscles and nerve of the frog into a complete circuit. Galvani emphasized in his thought the rôle of the nerve and the muscles; but Volta (1745–1827) then professor of physics at Pavia, soon proved that the *nerve* was not a necessary part of the circuit; two metals and the *muscle* were sufficient to produce the effect. Volta did not, however, stop here, but proceeded to show by means of a delicate electroscope and condenser, that when two metals, say zinc and copper, are each supported on insulating handles, then brought into contact for a moment and again separated, one of them (zinc) becomes positively electrified and the other (copper) negatively electrified. Early in the nineteenth century it came to be recognized, largely through the work of Davy and Faraday, that the contact of the two different metals in some way disturbs the electrical equilibrium of the circuit, that the decomposable fluid in some way restores the equilibrium and that during this readjustment the electric current flows. The most recent experiments of Lippmann, Millikan and Langmuir appear to confirm this general view. During the last twenty years of the eighteenth century all these phenomena were grouped under the head of "animal electricity;" but this experiment of Volta's put an end to animal electricity save in its legitimate sense, referring to the electric eel or other animals with electric organs. The next step was to intensify the slight but remarkable effect already obtained; this Volta did in two different ways; first, by piling up a series of cells



Alessandro Volta (1745–1827)
Italian physicist, inventor of the primary cell

as we would now call them, each made up of a zinc and a copper disk with a moistened disk of cloth between them; and secondly, by substituting for the moistened cloth a cup of acidulated water, and joining, through zinc and copper strips, a number of such cups in series. Volta described these results at length in a paper which he sent to the Royal Society of London in 1800. From this moment on, everyone interested began to produce for himself the curious physiological effects announced from Pavia; and shortly, many of the electrolytic, thermal, and magnetic properties of the electric current were well known. The popular interest awakened by these two types of the electric battery the "Voltaic pile" and the "crown of cups"—was tremendous. The pioneer stage of the Voltaic cell was over. Honors of all kinds were heaped upon this modest Italian physicist. Voltaire entertained him at his home near Geneva, Napoleon invited him to Paris, the French Academy and the Royal Society of London elected him to membership, an international congress of electricians meeting at Paris in 1881 named the unit of electromotive force after him, and now (September, 1927) the centennial of his death is being celebrated by an international congress of physicists at Como.

CHAPTER VIII

Discovery of the Nature of Heat

> "History is to society what memory is to the individual."
> —*Jour. Pol. Econ.*, xxxi, 739.

At this point, in a brief sketch of the rise of modern physics, one might very properly follow up the history of electrolysis and electromagnetism as it developed immediately following the discovery of the Voltaic cell. It seems preferable, however, to go back and gather up the threads which lead to modern views concerning the subject of heat; in order that one may learn what other questions in physics men were studying at the time when Gilbert, Gray, Franklin and their contemporaries were thinking about electricity, or while Galileo, Huygens and Newton were creating the science of dynamics.

As has been indicated earlier, the ancients contributed very little to the science of heat beyond what was known, in prehistoric times, by the men who discovered fire and used it to reduce certain metals from their ores. The one exception to this statement is perhaps the work of Hero and other Alexandrians who, about the beginning of the Christian era, used the expansion of air by fire, or by the sun's heat, to perform many mechanical operations and who also employed the reaction of a jet of air or steam to set a ball into rotation.

For Hero's description of these experiments see Woodcroft's *The Pneumatics of Hero of Alexandria*, pp. 57–72, translated from the Greek (London, 1851). It is possible, of course, to find the thermometer in the first of the two experiments mentioned above and the steam-engine in the second. The essential fact, however, appears to be that the study of heat was seriously taken up, for the first time, about the end of the sixteenth century when instruments distinctly intended for measuring temperature began to appear.

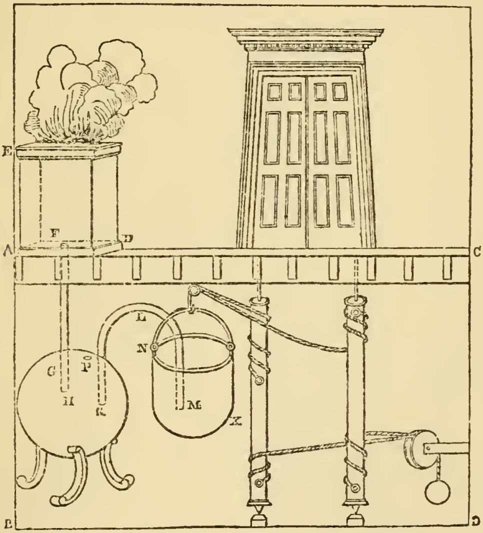


Fig. 8. Hero's Device for Using Heat from an Altar Fire to Open Temple Doors

The three fundamental ideas which we propose to trace are the principle of the thermometer, the conception of heat as a measurable quantity, and the nature of heat.

THE MERCURY THERMOMETER

The expansion of air—in any event, the rising of heated air over a hot body—must have been one of the earliest effects of heat observed. It is therefore quite natural that this phenomenon—the expansion of air—should form the basis of the earliest thermoscopes; and so we find it. Before one can measure differences of temperature, he must learn to tell whether one temperature is higher or lower than another.

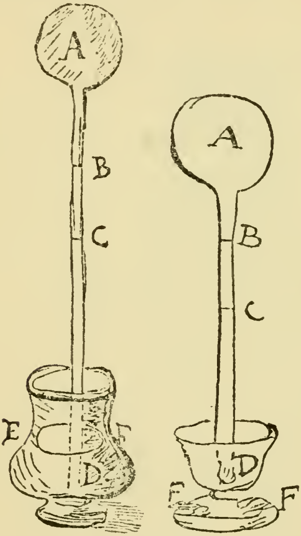


Fig. 9

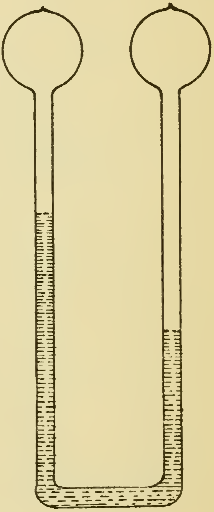


Fig. 10

Fig. 9. Castelli's Sketch of Galileo's Thermometer
Fig. 10. Father Schott's Differential Thermometer, 1657

It is a curious thing that Galileo, who appears first to have devised and used a thermoscope, never mentions the fact in any of his writings; but since Castelli, one of Galileo's ablest students, describes in great detail a thermoscope which Galileo showed him in 1603; and since another student of his, Viviani, reports the invention of this instrument by Galileo shortly after his arrival at the University of Padua in 1592, there seems to be no valid reason for doubting the statement that Galileo invented an instrument along the lines indicated in the accompanying figure, which is taken from a letter of Castelli's written in 1638. The device consisted merely of an air-filled bulb with the neck of the bulb inverted below the surface of a liquid. The lower liquid surface being exposed to air, the instrument was at once a baroscope and a thermoscope. It could hardly be called a thermometer; but it was an instrument which gave results independent of the individual observer; its indications are at least objective and not subjective.

A few years later, a glass bulb was filled with a liquid and the top sealed off from the air. A number of such thermometers made by the Florentine Academy—composed mainly of Galileo's pupils—are preserved in the Galilean museum in Florence.

Father Schott, in 1657, shut off the liquid from the atmospheric pressure in a U-tube by sealing a glass bulb on each end of the U-tube as indicated in fig. 10. He then had a device which showed differences of temperature between the two bulbs; the same instrument is described by J. C. Sturm (1635–1703) in his *Collegium Experimentale*, published at Nürnberg between the years 1676 and 1685.

The next step, a minor one, appears to have been the substitution of a liquid for a gas as the thermometric substance; this was done by Jean Rey, a French physician; but it was left for the Florentine Academy to make the earliest sealed-in, liquid-in-glass thermometers of which we have any definite record. All that was needed to turn these Florentine thermometers—which are veritable *objets d'art* so far as glass work is concerned—into modern instruments was a scale that could be duplicated by independent observers and thus make measurements in different places and at different times strictly comparable.

The brief existence of the Florentine Academy covered only ten years. Its proceedings were printed in 1667; but more than twenty years were to elapse before any satisfactory thermometric scale was proposed.

Robert Hooke, secretary of the Royal Society, had found the melting point of ice to be very constant and proposed this, in 1664, as "a standard temperature;" Huygens, the year following, made the same proposal for the boiling point of water; but neither of these nimble minds appears to have realized that *two* fixed points are an absolute necessity if the degrees of temperature are to be definitely defined. The two fixed points appear to have been introduced in 1688 by Dalancé who adopted the melting points of ice and butter as the two temperatures in question, and used linseed oil as a thermometric substance.

It is to Fahrenheit (1686–1736), however, that we owe the modern mercury-in-glass thermometer with a scale depending on melting ice and boiling water. The size of the degrees are, of course, arbitrary. Fahrenheit selected (1714) the temperature of a mixture of salt and ice as zero, also the interval between melting ice and boiling water as 180°, thus making the freezing point of water 32°F. It has been found more convenient by most experimenters to divide the fundamental interval into one hundred degrees as advised, in 1742, by Anders Celsius, professor of astronomy at Upsala.

The close of the nineteenth century saw the scale of the glass thermometer greatly extended at each end. For measuring very low temperatures, mercury was replaced by pentane which does not freeze until it reaches a point 200°C. below zero, which is 15°C. below the boiling point of liquid air. For measuring temperatures higher than that of boiling mercury, the space above the mercury in the thermometer is filled with nitrogen under pressure, thus raising the boiling point so that such a thermometer is practicable up to 500°C.

THE AIR THERMOMETER

Before the end of the eighteenth century it had been well established that the coefficient of expansion of any liquid, even mercury, is more or less irregular; that is to say each liquid has its own coefficient of expansion different from each other and no one of them is uniform. With the same fixed points, each liquid was found to give its own thermometric scale. In the case of the permanent gases, however, each has nearly the same coefficient as the other, and within wide limits, the coefficient is practically constant, so far as variations of pressure and temperature are concerned. J. H. Lambert (1728–1777) a German physicist, mathematician and astronomer, appears first to have appreciated the valuable properties of air as a thermometric substance. These were set forth in a posthumous volume.[1] It was more than half a century later, however, that the French physicist, H. V. Regnault (1810–1878), prince of experimentalists, turned the gas thermometer into an instrument of precision by comparing the coefficients of various gases with each other and with that of mercury, correcting for the expansion of the glass, etc., and thus prepared the way for the greatest advance of all in scientific thermometry, the use of the absolute scale of temperatures, which is independent of any thermometric substance and which will be considered a little later.

In 1887, the *International Committee on Weights and Measures* adopted as the standard scale of temperatures the centigrade scale of the hydrogen thermometer, which between 0°C. and 100°C., differs from the absolute scale by only a few thousandths of a degree; while at 1100°C. the difference is only about 1°. To standardize a mercury thermometer it became necessary to compare its readings with those of a hydrogen thermometer, an operation calling for a high degree of skill.

The measurement of high temperatures—say those above 500°C. has recently become a large and almost independent science, based mainly upon the effects which temperature-changes produce in *electric resistance*, *thermo electric E. M. F.*, and *energy radiated* by the body whose temperature is in question—a subject into which it is not proposed here to enter. Suffice it to say that the resistance thermometer originally constructed by Sir

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[1] *Pyrometria*, Berlin, 1779.

William Siemens in 1871, and afterwards perfected by H. L. Callendar of London and a host of other investigators, is easily capable of indicating a change of 0.°0001C.

HEAT AS A MEASURABLE QUANTITY

From early Greek times, men have filled space with a hypothetical ether whenever they found it convenient for their explanations. Thus Descartes, attempting to explain everything on a mechanical basis, filled all space with vortices and made the ether a *plenum* which transmits light as a pressure; while Newton's theory of universal gravitation had nothing to say about ether or any other substance between two attracting bodies. Fresnel thought of the ether as an elastic solid; and Lord Kelvin, in his *Baltimore Lectures* (1884) made a famous attempt to apply dynamics to the luminiferous ether and thus explain the ordinary phenomena of light.

In the early part of the eighteenth century, when it was still supposed that light and heat were composed of corpuscles of ordinary matter, very fine and imponderable however, it was discovered that a sheet of plate glass would permit light to pass through but would prevent the passage of heat. This at once led to the view that these two imponderables differ one from the other; that light corpuscles are not the same as heat corpuscles. The most accurate experiments did not indicate that heat produced any increase of weight.

Differences between the electric and magnetic fluids had already been pointed out by Dr. Gilbert. A magnet does not require friction, as sulphur does, to excite it into activity; magnetic action between two bodies is not affected by immersing them in water, as is the case with electrified bodies. The result of all these various views was to place on the list of elements the following four substances—all imponderables: (1) *Electricity*, (2) *Magnetism*, (3) *Light*, (4) *Heat*.

Light and heat were included among the elements not only by Boyle but also by Lavoisier[2] as late as the close of the eighteenth century; and these are the two men above all others to whom we owe the modern idea of a chemical element.

We have already considered the early history of the first three of these imponderables and now proceed to inquire how this fourth imponderable—known for a full half century as *caloric*—showed itself to be a measurable quantity. It was perfectly clear in those earlier days, say at the middle of the eighteenth century, that when the temperature of a body rose it was because more caloric had been added to it; a body expanded on heating because the caloric which had been added pushed the particles farther apart.

The Florentine academicians (1657–1667) made an elaborate series of observations upon the various effects of heat; and, from their records, it would appear that they had noticed how much more heat is required to raise the temperature of a given weight of water through any given range than an equal weight of mercury through the same range. Nevertheless the first man to make the distinction between *temperature* and *quantity of heat* perfectly clear appears to have been the Scottish chemist, Joseph Black (1728–1799) of Glasgow who observed that when ice melts it takes up a quantity of heat without suffering any change of temperature whatever; and since the imponderable caloric here produces no change of temperature, Black assumed that it combined with the ice and thus became *latent* in the water. "Considered as the cause of warmth we do not perceive its presence; it is concealed or latent, and I gave it the name of *latent heat*." Black's *Lectures* (I, p. 157, 1803). Black went further, devised an ice calorimeter and proved that for every pound of ice melted it was necessary to cool an equal mass of water from 172° to 32°F., which is equivalent to cooling it through 77.8°C. He also demonstrated that the evaporation of any given mass of water at the normal boiling point requires an amount of heat sufficient to raise the temperature of 445 times that much water through 1°C. Few things in the whole range of physics are more truly astounding than this discovery of Black's that a pound of ice at 0°C., if mixed with a pound of water at 79.77°C., will result in two pounds of water at 0°C. Black thus showed that we have here two natural units of heat: either (i) the amount of heat required to change one unit of ice into a unit of water without change of temperature or (ii) the amount of heat required to raise unit mass of water 1°. The second unit is the one everywhere used today in the form of the "15°C. calorie" and the "mean Centigrade calorie"; though, as late as 1896, H. A. Rowland highly recommended to the British Association for the Advancement of Science the unit based on melting ice, since this is independent of any system of thermometry.[3]

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[2] *Elements of Chemistry*, 1789.

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[3] For Rowland's letter, see Glazebrook's Dictionary of Applied Physics, I, p. 494.

The next step—a perfectly natural one—had, so to speak, already been taken. It consisted in the discovery that the amount of heat required to raise a mass of water 1° and the amount required to heat an equal mass of another substance 1° varies greatly from one substance to another. Thus was introduced the idea of *specific heat;* and the science of *calorimetry* was fairly launched. A large number of beautiful calorimeters have been devised since the time of Black. Space will allow us to mention only two: that of R. Bunsen (1871) who measures the amount of ice melted, not by the balance, but by its change in volume, it being well known that a volume of water on freezing increases by ninety-two parts in a thousand; and that of Professor John Joly (1886) in which he cleverly measures the amount of heat imparted to a body by weighing the amount of steam which the body will condense upon itself during the heating.

Another set of calorimeters—the so-called "continuous flow" type—have been perfected for measuring the *rate* of heat production such as that of Junker for a gas-flame or that of Callendar and Barnes for an electric current.

THERMODYNAMICS.

The first law of thermodynamics

According to the caloric theory, bodies become cooler as they give up caloric, unless they happen to change their state as in the case of water becoming ice; they become hotter as they take in caloric, unless, as in the case of an expanding gas or a vaporizing liquid, the caloric becomes *latent.* But whence comes the caloric in the case of

JULIUS ROBERT MAYER (1814–1878)
Derived the First Law of Thermodynamics in an *a priori* way in 1842

bodies heated by rubbing? If heat be a material substance—caloric—where does this substance come from in the case of friction? This was the question taken up in earnest by Count Rumford (1753–1814), a British-American man of science, just before the close of the eighteenth century when he was minister of war in Bavaria. In boring brass cannon by horsepower, Rumford found that he could produce an unlimited amount of heat by using a dull or blunt tool with a comparatively small amount of abrasion of the brass; and in a paper which he presented to the Royal Society in 1798, he protests the view that the small mass of brass turnings have given up enough caloric to account for the large amount of heat which makes its appearance during the process of boring. Rumford's argument was appealing but not quite conclusive; for the simple reason that the brass turnings were not in the same "state" as when they were a part of the solid brass cylinder, although their specific heat is the same as that of brass. In the year following, Sir Humphry Davy (1778–1829) sought to establish the view of Rumford—the immateriality of heat—by rubbing two pieces of ice together and thus melting a portion of the ice.

The argument of Davy is, in one sense, more cogent than that of Rumford since the specific heat of water—which may be here regarded as the abraided material—is nearly twice that of ice. The man, however, who first established the mechanical theory of heat on a solid experimental basis is the English physicist, J. P. Joule (1818–1889) of Manchester. He employed a variety of different methods for producing heat in a body by doing work upon it. In every case he measured the work done and also the heat produced; and always found a strict proportionality between these two. His results were summarized and presented to the Royal Society in 1849; and they establish beyond question the fact that whenever mechanical work is expended in overcoming friction, a strictly proportional amount of heat appears, one British Thermal Unit appearing for every 772 foot pounds of work expended. The idea that heat is a *substance* which can be extracted from any body in indefinitely large quantities promptly disappeared and was replaced by the doctrine that heat is a form of energy, and that all the various transformations of heat are governed by the principle of the conservation of energy. This theorem, when thus quantitatively applied to heat, is known as the First Law of Thermodynamics.

The second law of thermodynamics

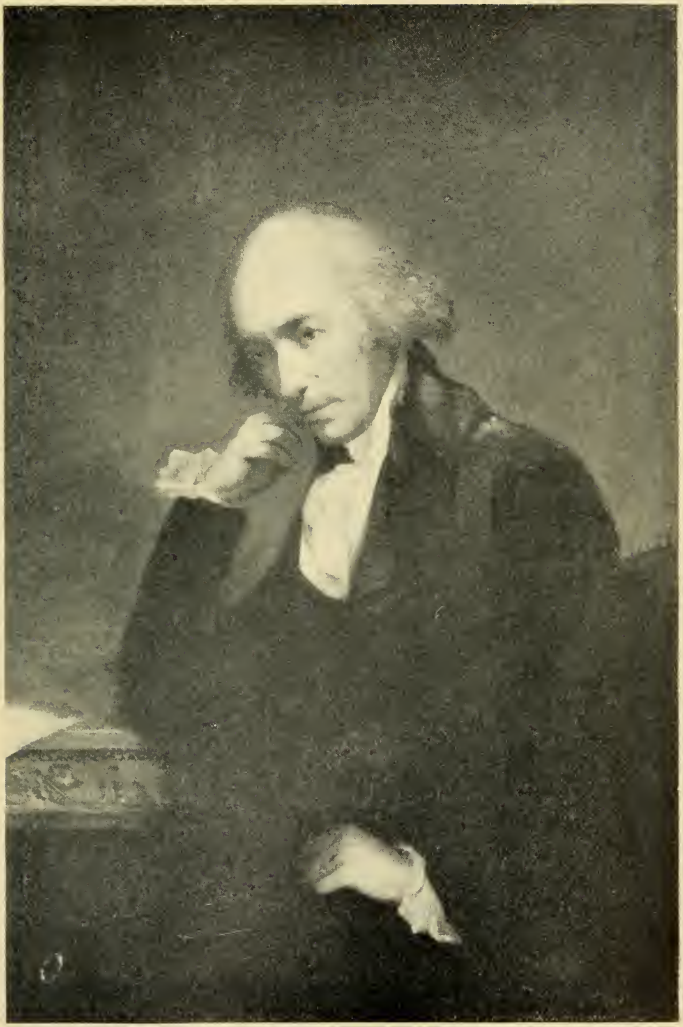
Between the early observations on the expansive power of steam and of hot air—those, say, of Hero about the beginning of the Christian era—and the invention of the first commercially successful steam-engine—that which Thomas Savery patented in the reign of William and Mary (1688–1702)—intervene many interesting experiments, by Della Porta (1601), Solomon de Caus (1612), Branca (1629), Marquis of Worcester (1663), Huygens (1680) and others, upon the properties of heated vapors or gases; but none of these has an importance of high order. Savery employed a metal vessel—a displacement chamber—in which he used the pressure of steam to drive the water out and then after turning the stop-cock used the condensation of steam to produce a vacuum in this chamber; and, once having a vacuum, he had only to turn another stop-cock in order to connect this vessel by a pipe with water at a lower level and allow the atmospheric pressure to lift the water into the empty chamber. The steam was furnished by an adjacent boiler. In 1690, the year of Huygens' *Treatise on Light*, Denis Papin (born 1647), a French physicist and assistant to Huygens, introduced a piston and cylinder instead of the displacement chamber of Savery. Papin thus had a single acting steam pump; but the same cylinder was used for steam and for the water which was pumped. A few years later (1705) Thomas Newcomen, devised an engine in which the cylinder and piston were free from the water to be lifted. The steam from a detached boiler was used to lift the piston in the cylinder and then a jet of water was introduced to condense the steam; in this manner Newcomen obtained, by a more economical process, a reciprocating motion which could be applied to do work of any kind. As soon as the automatic device for opening and closing the valves was added to Newcomen's engine, we had the machine as it came into the hands of James Watt in 1763.

Watt (1736–1819) was not only a trained and skillful instrument-maker, but also a profound student of every problem he took under consideration—a man to whom Sir Walter Scott alludes as one of "our Northern Lights." Consequently when a Newcomen engine came into his hands for repair, these scholarly instincts led him at once to inquire how it might be improved. He immediately detected the immense waste of energy in alternately heating and chilling what he called the *steam-vessel*—what we now call the *cylinder* of the engine; to avoid this waste, he devised and, in 1769, patented, a separate cooling chamber—the modern *condenser*—and jacketed the cylinder with wood. The use of this condenser clearly demanded some means of keeping down the back pressure from it; this need Watt early appreciated and supplied by his invention of an *air-pump*.

Thirteen years later, he realized the possibility of applying steam to both sides of the piston-head and thus getting two useful strokes out of every cycle instead of one as in the *single acting* Newcomen engine. Another valuable feature, introduced in 1782, and one which transformed this *double-acting* engine into its modern form is that of expansive working of the steam; in other words, he automatically shut off the connection between the boiler and the cylinder at an instant when only a part of the stroke had been completed and thus allowed the hot steam to accomplish the remainder of the stroke by expansion.

During the first quarter of the nineteenth century, the locomotive was perfected to such an extent that in October of 1825 regular trains began to run between Darlington and Stockton in England; while in America, a similar distinction is claimed by the Baltimore and Ohio road which established a regular schedule, using a steam locomotive, in 1830. By the middle of the nineteenth cen-, tury, the steam-engine had been compounded, following a suggestion of J. C. Hornblower made as early as 1781.

So far all progress in the development of steam power had come in a purely empirical manner, save possibly



James Watt (1736-1819)
Inventor of the modern condensing and expansive working steam engine

a few suggestions as to the latent heat of steam which Joseph Black turned over to James Watt during the time (1757 to 1766) when they were both at the University of Glasgow.

It was in the year 1824 that Sadi Nicolas Léonard Carnot (1796–1832), an eminent French physicist—grandson of the great French general and uncle of the late French president of that name—published his *Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance*, and thus established the theory of the steam-engine, and indeed of all heat engines. This brilliant member of one of the most ancient and celebrated families of France died at the early age of thirty-eight and published only this single memoir during his life; but the problem which he there raised and solved is one of the most fundamental in the entire range of physical science. It is this: How much work can be obtained from a given amount of heat? Some thought an indefinitely large amount; but Carnot, taking a hydraulic power-plant as his model, argued that in every heat engine there is a fall of temperature—corresponding to the fall of water—and that there can be no transformation of heat into work without a *source* and a *sink* of heat at different temperatures.

In order to give this general principle quantitative expression, Carnot considered the efficiency of the engine and proved that this is a maximum when the cycle of operations of the machine is reversible. The cycle which he employed and which always goes by his name is bounded by two isothermal and two adiabatic curves; and it has this great merit that, at the end of the cycle, the working substance is left in precisely its initial condition. One does not, therefore, have to think about the so-called *intrinsic* energy, that is, the energy residing in the working substance. He has merely to consider the heat, H, given to the engine, the heat, h, rejected by the engine, and the heat, W, converted into work by the engine.

Carnot thought, in violation of the principle of the Conservation of Energy, that the engine rejected the same amount of heat which it received. Heat measurement is the *bête noire* of the physical laboratory; and it was not until many years later that the French engineer, Hirn, proved, by experiment, that $h<H$. Nevertheless, Carnot was able to establish the theorem that *the efficiency,* $\frac{W}{H}$, *of an engine working between any given pair of temperatures is a maximum when the processes of the engines are reversible.* The full import of this principle was first made clear by R. Clausius in a paper presented to the Berlin Academy in 1850, where the fundamental fact is shown to be that *Heat cannot, of itself, pass from a colder to a hotter body;* a statement which is now known as the second law of thermodynamics. If heat is made to pass from a cold body to a hot one—and this can easily be done by use of the proper machinery—the process, Clausius showed, is always accompanied by a greater, or at least by an equal, fall of heat from a hot to a cold body elsewhere.

Looked at from another point of view, the facts which Clausius included in his second law were the analogues of such facts as the following: A clock, left to itself, runs down. Two different gases, when brought together, diffuse each into the other. An iron rod heated at one

Zygmunt Florenty Wroblewski (1845–1888)
Eminent Polish physicist who first succeeded in liquefying air

end and cooled at the other, tends when left alone to equalize its temperature. To cover all these cases of "running down," Clausius introduced the term *entropy* and defined it in such a way that the second law amounts to saying that *the entropy of the universe tends toward a maximum.* Any change in an isolated system is always in the direction of greater entropy.

It is only in recent years that this law—now the foundation stone of physical chemistry—has received an explanation. To Willard Gibbs (1839–1903) and Ludwig Boltzmann (1844–1906)—creators of the science of statistical mechanics—we owe the idea that the second law of thermodynamics is merely a statement of the general fact that the temperature changes which take place in an isolated system of bodies are merely those which are most probable when the state of the system is one which is far removed from a state of equilibrium.[4]

Carnot had, however, done more than merely establish the above theorem; he had pointed out that the maximum efficiency of an engine working through any fixed small range of temperature, say a fraction of 1°C., is a function of the temperature at which the heat is received and depends upon nothing else. In 1848, twenty-four years after the appearance of Carnot's paper, Lord Kelvin made the brilliant suggestion that since the efficiency of such an engine is independent of the working substance and is a function of the temperature alone, it is possible to define temperature in a way which is independent of the nature of the substance employed in the thermometer. Such a scale Kelvin and Joule proceeded to determine in terms of the air therometer. The size of the degrees and the zero of the scale were still arbitrary. The degrees were chosen of the same size as those of the centigrade scale and the melting point of ice was called 273°C. Of all the remarkable achievements of Lord Kelvin, the establishment of this system of *absolute temperature* is perhaps the one of highest permanent value. The experiments of Kelvin and Joule are known as the porous plug experiments; and they have shown that the hydrogen thermometer scale is practically identical with the absolute scale, and have thus placed the science of thermodynamics on a solid foundation. The fundamental equations of the subject were shortly afterwards (1850) worked out by Clausius and Rankine in practically the same form in which we have them today.

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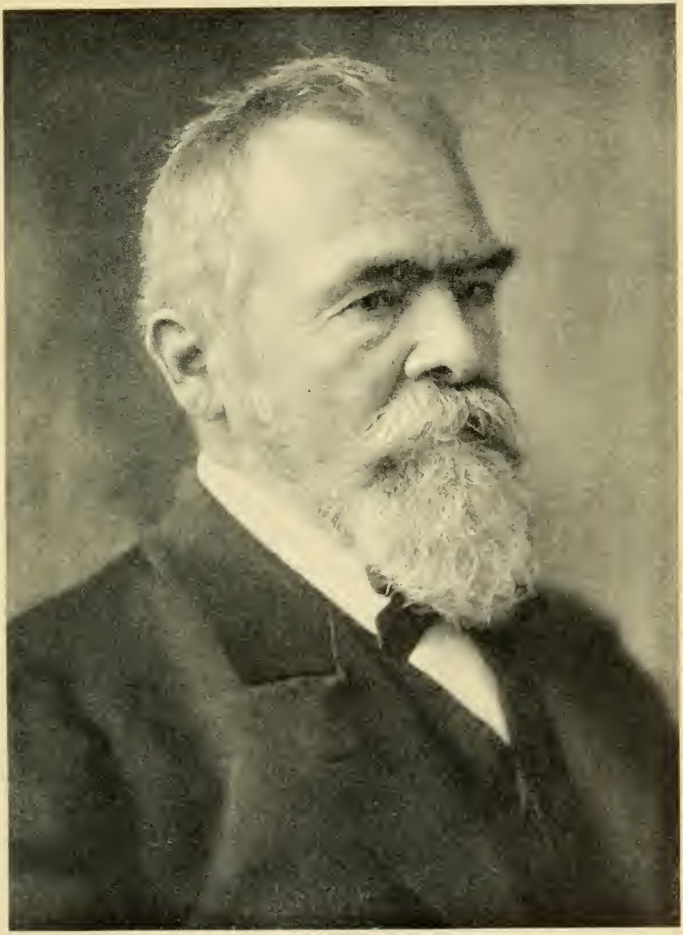
[4] For further historical details, see Clausius' *Mechanical Theory of Heat*, Chapter XIII. Translated by W. R. Browne. Macmillan, 1879.

THE CONDUCTION OF HEAT

Just how heat is handed on from one portion of a body to another has always been, and is yet, one of the pending problems of physics. A copper wire is built up, as we now know, of copper crystals, a set of tethered copper atoms; but whether the heat is passed on by the vibrations of these atoms or by some motion of the electrons which are constituent parts of these atoms is a mooted question.

The manner in which physicists handle a case of this kind where they are dealing with quantities and processes they do not understand, is well illustrated by the description of the flow of heat given by J. B. J. Fourier



Karl Ritter von Linde (Born 1842)
Inventor of the process now used everywhere for the production of liquid air

(1768–1830) in his *Théorie analytique de la chaleur*, published in 1822. In this justly celebrated volume, Fourier shows that, without knowing anything about the nature of heat or about the structure of matter, one may summarize the experimental facts of heat conduction by saying that *the rate at which heat is transmitted by conduction is directly proportional to the temperature gradient;* and this law has been thoroughly justified by a century of experiment since its enunciation by Fourier. The innocent bystander at once inquires what is meant by the "rate of transmission of heat." Here Fourier's definition is, the quantity of heat transferred across unit area of cross-section of the substance in unit time. The temperature gradient also calls for definition. This means the fall of temperature per unit length measured in the direction of the heat flow. The ratio of these two quantities—heat flow to temperature gradient—he called the *thermal conductivity*. Fourier expressed this law in the form of a simple differential equation—a method universally employed since the time of Newton as the most definite and most general form in which the laws of nature can be set forth. The great value of Fourier's contribution lay in his clear definition of thermal conductivity, and in his application of the law to numerous concrete cases, such as cooling walls, cylinders, spheres and rings.

Only five years after the appearance of the *Théorie analytique de la chaleur*, a German professor of mathematics in a Jesuit college at Cologne, Georg S. Ohm (1787–1854) enunciated a similar, or rather an identical, rule for the flow of electricity. The identity is at once seen on substituting *electric current* for *flow of heat*, and *electric potential for temperature.* The proportionality constant in Ohm's law is known as *electrical conductivity.* Here again, without knowing the nature of electricity, it is possible to use Fourier's equation to describe and predict a vast number of important phenomena. Diffusion between two liquids is also described by Fourier's law. Here *density-gradient* replaces *temperature-gradient* and *flow of diffusing substance* replaces *flux of heat.*

If one seeks an explanation of the rapid advance of physics, as compared with metaphysics, during the last three hundred years, he will probably find it in the fact that, in general, physicists are content, and metaphysicians are not content, to limit themselves to experimental facts and to principles which they understand and to confess ignorance concerning all other matters.

The career of Fourier, like that of d'Alembert, is a notable example of what can be accomplished under adverse circumstances. Son of a French tailor, left an orphan at eight years of age, educated in a military school conducted by Benedictine monks, he was without rank and without wealth; and on this ground, was refused admittance to his chosen field, the artillery, in spite of excellent recommendations from the great geometer, Legendre. The minister of war not only denied him the privilege of an entrance examination but accompanied his denial with the biting remark that a lad of his poverty and low degree "could not enter the artillery though he were a second Newton."

In the face of these dire circumstances Fourier, at thirty, was one of the *savants* who accompanied Napoleon to Egypt; a little later he was successively professor in the *Ecole normale* and the *Ecole polytechnique*—then, as now, two of the leading institutions of France; at forty-nine, he was received into the French Academy and was shortly afterward elected to the perpetual secretaryship of this worthy assembly.

CHAPTER IX

THE DISCRETE NATURE OF MATTER

"Aime la vérité, mais pardonne à l'erreur"
—VOLTAIRE, *Discours sur l'Homme.*

It now becomes necessary to go back and gather up some of the threads which have led us to the modern view that matter, unlike space and time, is discontinuous, i.e., made up of discrete particles. The history of thermal ideas, so far as we have followed it, has involved mainly changes of temperature, volume, pressure, and conductivity; nowhere, as yet, have the experimental facts demanded that we consider gases, liquids or solids as anything but continuous.

The ancients had even less evidence than we for thinking that matter possesses a grained structure. Just what evidence weighed most with them we shall probably never know. It was possibly such facts as the rapid diffusion of odors, the expansion and contraction of air, and the various forms of crystals that led Leucippus (born *c.* 500 B. C.) and Democritus (born 465 B. C.) to assume the set of eternal, indivisible, invisible, homogeneous, and incompressible atoms already described in an earlier chapter.

There was nothing in the four elements of Empedocles to suggest a grained structure of matter. Nor did Lucretius, in describing the views of Epicurus and Democritus, add any new experimental evidence for the discrete nature of matter.

All the four elements of Empedocles and the fifth immaterial element—’ουσία—the quintessence—added by Aristotle are principles rather than substances.

It is not indeed until late medieval—or perhaps modern—times that the heterogenous character of matter is cogently discussed.

Pierre Gassendi (1592–1655), a French philosopher and mathematician, is often spoken of as a pioneer in modern atomic theory; but it is difficult to find in his work much more than a resurrection of the ideas of Democritus and Epicurus. Gassendi resembles the two Bacons in defending the observational and experimental method, a service of no mean order, it must be confessed; but he apparently considers heat to consist of small particles of a heat fluid—caloric—in contrast to Hooke, Rumford and others who have shown by experiment that heat consists in the motion of particles of ordinary matter.

THE KINETIC THEORY OF GASES

The man who first took up the observed properties of a gas and attempted to explain them on a simple mechanical basis was Daniel Bernouilli (1700–1782), one of the most distinguished members of this celebrated Dutch-Swiss family. It is in the tenth chapter of his great treatise, *Hydrodynamica*, published at Strasbourg in 1738, that he sets forth the fundamental ideas of the kinetic theory. The first six sections contain the gist of the matter; they run as follows:

> §1. "In considering the subject of elastic fluids, it is permissible to assign to them a constitution such as agrees with their known

properties and such as will lead us to the discovery of properties hitherto unknown. Of the known properties the most important are (i) They have weight. (ii) They expand indefinitely if they are not enclosed. (iii) As the pressure is increased, they are more and more compressed."

"It is to air thus constituted that our present considerations mainly refer.

§2. "Imagine a vertical cylindrical vessel *ACDB* (fig. 11) in which fits a movable piston *EF* upon which there is placed a weight *P*.

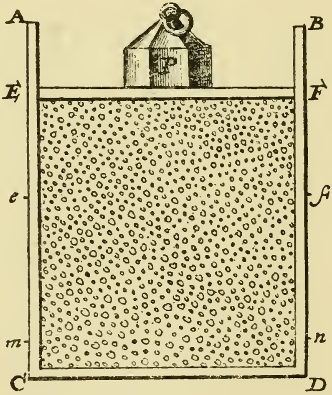


FIG. 11. FROM BERNOUILLI'S "HYDRODYNAMICA," PAGE 200

Let the enclosure *ECDF* contain some very small particles moving hither and thither with extreme rapidity. It is these corpuscles which impinge upon the piston and which by their continually repeated impulses sustain it that constitute the elastic fluid; a fluid which expands whenever the weight *P* is removed or diminished; which is compressed whenever the weight is increased; and which also weighs down upon the horizontal base *CD* just as if it possessed no elasticity whatever. For whether these particles are at rest or in motion they do not change in weight; and thus the base of the vessel sustains both the weight and the elasticity of the fluid.

"Such a fluid, since it possesses the outstanding properties of air, may be substituted in thought for air so that we may explain the properties of air already known and may obtain some light upon these properties which are as yet not fully understood.

§3. "The particles in the cylindrical cavity we may consider infinite in number; and when they fill the space *ECDF* we may say that the gas is in its natural state; and all measurements are referred to the dimensions of this space. Then the weight, *P*, which holds the piston head in the position *EF*, does not differ in pressure from the superincumbent atmosphere which may therefore in the following discussion be indicated by *P*.

"It is to be noted that the minimum value of this pressure is equal to the absolute weight of the vertical cylinder of atmosphere resting upon the piston as some authors have already hastily stated; but this pressure is really a fourth proportional to the surface of the earth, the area of the piston *EF* and the weight of the whole atmosphere upon the surface of the earth.

§4. "Let us find the weight π which is required to compress the gas *ECDF* into the space *eCDf*, it being assumed that the speeds of the particles are the same in the natural and in the compressed state. Put $EC = 1$ and $eC = s$. Now when the piston *EF* is brought down into the position *ef*, it produces an increase of pressure upon the fluid for two reasons; *first* because there are now more particles per unit space; and *second* because each particle delivers its impulses more frequently. In order to compute this increase correctly, we shall suppose that, so far as the first cause is concerned, the particles are at rest and that the number of those which are contiguous to the piston in the position *EF* is *n*. The corresponding number when the piston is in the position *ef* will be

$$n\Big/\left(\frac{e\,C}{E\,C}\right)^{2/3} = n/\,s^{2/3}$$

"It must be remarked that the fluid we are considering is no more compressed in the lower part of the vessel than in the upper, at least so long as the weight *P* may be taken to be infinitely large compared with the weight of the gas itself. Hence it is clear that, on this ground, the pressures of the fluid will be to each other as the number n to $n/s^{\frac{2}{3}}$; or, as $s^{\frac{2}{3}}$ to 1.

"So far as concerns the increase of pressure brought about by the *second* cause, this is to be found from a consideration of the motion of the particles; and it is evident that the impacts will take place more frequently in proportion as the particles are nearer to each other. It is obvious indeed that the number of impacts will be inversely proportional to the mean distance between the surfaces of the particles. These mean distances are determined as follows: We shall assume the particles to be spheres, and shall indicate by D the mean distance between centers of spheres when the piston is in the position EF. Let us call the diameter of the spheres d; then the mean distance between the surfaces of the spheres will be $D - d$. It is evident that when the piston is in the position ef the mean distance between centers of spheres will be $D\sqrt[3]{s}$ and hence the mean distance between surfaces of the spheres $D\sqrt[3]{s} - d$. Therefore, so far as the second cause is concerned, the pressure of the gas in its natural state, $ECDF$, will be to the pressure in its compressed state $eCDf$ as $\dfrac{1}{D - d}$ is to $\dfrac{1}{D\sqrt[3]{s} - d}$ or as $D\sqrt[3]{s} - d$ to $D - d$. When both causes act together the pressures will be as $s^{\frac{2}{3}} \times (D\sqrt[3]{s} - d)$ to $D - d$.

"For the ratio D/d we may however substitute one which is more easily understood. Imagine the piston EF when depressed by an infinite weight to assume the position mn in which all the particles touch; then if we denote the distance mC by m the ratio of D to d will be that of 1 to $\sqrt[3]{m}$. Substituting the value of this ratio, one finds the pressures of the natural gas $ECDF$ and the compressed $eCDf$ to be related as $s^{\frac{2}{3}} (\sqrt[3]{s} - \sqrt[3]{m})$ to $1 - \sqrt[3]{m}$; or as $s - \sqrt[3]{ms^2}$ to $1 - \sqrt[3]{m}$; and therefore

$$\pi = P\left(\frac{1 - \sqrt[3]{m}}{s - \sqrt[3]{m\,s^2}}\right)$$

§5. "Experiment indicates that air can be enormously compressed and its volume reduced almost to zero. If we put $m = 0$, then

$$\pi = \frac{P}{s}$$

from which we see that the compressing weights are almost in the inverse ratio of the spaces which the gas in its different degrees of compression occupies. This law is certainly correct for air which is less dense than at atmospheric pressure; and, indeed, it may hold for air which is considerably more dense, but I have not investigated this matter. Up to the present, no experiments of sufficient accuracy have been made upon this subject. The quantity m needs to be determined with high accuracy and with the air tremendously compressed, taking care to keep the temperature strictly constant during compression.

"§6. The elasticity of air is increased not only by compression but also by increase of temperature [*ab aucto calore*]; and since it is established that the temperature [*calorem*] increases as the internal motion of the particles increases, it follows, in accordance with our hypothesis, that when the elasticity of the air is increased, without any change of volume, the motion of the air particles becomes more intense; for it is clear that the more rapid the motion of the air-particles, the more weight P will be required to hold the gas in the position [*situ*] *ECDF*. In like manner, it is easy to see that the weight must be proportional to the square of this velocity, because, when the velocity increases, the number of impacts and the intensity of these impacts each increase, and each proportionally to the weight P.

"If, therefore, we denote the speed of the air particles by v, the weight which is just capable of holding the piston in the position EF will be Pv^2; and, in the position ef, $Pv^2\left(\frac{1 - \sqrt[3]{m}}{s - \sqrt[3]{ms^2}}\right)$; or, very approximately $\frac{Pv^2}{s}$ since, as we have seen, m is a number which is exceedingly small in comparison either with unity or with s."

One has here evidently more than a mere adumbration of the kinetic theory of gases; for the equation $\pi\sigma = P$

is practically Boyle's law; and the proportionality between pressure and the square of the molecular velocities is essentially the law of Charles and Gay-Lussac. Nevertheless one misses from Bernouilli's account any accurate specification of what is meant by the "velocity of the gas particles," or by pressure, or by temperature. All these were to come a hundred years later. Bernouilli may therefore be said to have drawn the first rough quantitative sketch of the kinetic theory. His view like the views of Hooke, Boyle and, later, Rumford, stands in marked contrast to those of Gassendi, Boscovitch, and Marat; for the former believed heat to consist in the motion of small particles of ordinary matter, while the latter believed in a separate "heat fluid" or caloric.

It was three score and ten years after the appearance of Bernouilli's gas theory that the atomic structure of matter was established by Dalton (1808); and it was ninety years after Bernouilli's work that Avogadro (1828) first distinguished between the physical unit which we call the molecule and the chemical unit which we call the atom and set forth his hypothesis that, under equal pressures and temperatures, equal volumes of the different gases contain an equal number of molecules; but it was 110 years before the first new contribution to the gas theory; and this was made by James P. Joule in a paper, entitled "Heat and the Constitution of Elastic Fluids," read before the Manchester Literary and Philosophical Society, October, 1848. Here Joule employs his own experiments, showing that heat and mechanical energy are convertible, combined with the ideas of Bernouilli (without, however, mentioning his name) to compute the speed at which the particles of a gas must move, at a given temperature, in order to produce atmospheric pressure. Joule thus obtains for the square root of the mean square speed of hydrogen 6055 feet/second at the temperature of melting ice. Within a decade following Joule's paper, the foundations of the gas theory were completed by Krönig and Clausius. A. Krönig (1822–1879) showed[1] that, not only Boyle's law, but also the laws of Gay-Lussac and Avogadro, as well as the variation of speed with molecular weight and some of the experimental results of Joule follow from the kinetic theory of Bernouilli.

In the year following, R. Clausius (1822–1888), writing from Zürich, showed[2] that it was necessary to amend the kinetic theory by introducing molecular rotations and intramolecular motions, in addition to the purely translatory motion of Bernouilli and Krönig, in order to account for the entire heat present in the gas. The partition of energy among the various degrees of freedom of the molecule Clausius sets forth as follows:

> "Conceive a number of molecules whose constituents are in active motion, but which have no translatory motion. It is evident the latter will commence as soon as two molecules in contact strike against each other in consequence of the motion of their constituents. The translatory motion thus originated will, of course, occasion a corresponding loss of *vis viva* in the motion of the constituents. On the other hand, if the constituents of a number of molecules in a state of translatory motion were motionless, they could not long remain so, in consequence of the collisions between the molecules themselves, and between them and fixed sides or walls. It is only

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[1] *Poggendorff's Annalen*, **99**, p. 315, 1856.

[2] *Poggendorff's Annalen*, **100**, p. 253, 1857.

when all possible motions have reached a certain relation towards one another, which relation will depend upon the constitution of the molecules, that they will cease mutually to increase or diminish each other."

After pointing out that "the assertion that the true specific heat of a gas is constant is simply equivalent to the assertion that the total *vis viva* in the gas has a constant ratio to the *vis viva* of the translatory motion which serves as a measure of temperature," Clausius proceeds to lay down the various conditions which must be satisfied by a perfect gas, namely the negligible volume of the molecules, infinitesimal duration of contact, and vanishing force of attraction or repulsion between molecules.

The kinetic theory was now in a position to explain not only the ordinary gas laws of Boyle, Charles, Avogadro and Dalton; but also the phenomena of evaporation, diffusion and the three states of aggregation. From this theory flows naturally, as Clausius shows, not only the fundamental gas equation $p\,v = m\ n\ u^2/3$, but also the value of the ratio of the specific heats at constant volume and constant pressure, viz., 1.421.

From this point on the dynamical theory of gases developed rapidly in the hands of Clerk Maxwell,[3] Boltzmann,[4] Jeans[5] and others and has become an almost independent science quite beyond the range of this sketch.

THE ATOMIC THEORY

No historical sketch of the evidence for the discrete nature of matter can omit some consideration of the

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[3] *Philosophical Magazine*, January and July, 1860.

[4] *Vorlesungen über Gastheorie*, 1912.

[5] *Dynamical Theory of Gases*, 1904.

Ludwig Boltzmann (1844–1906)
Mathematical physicist of Vienna; outstanding investigator in the kinetic theory of gases

facts which led men of science everywhere to adopt the views enunciated by John Dalton (1766–1844) near the beginning of the nineteenth century. Among the Greeks, the atomic theory signified not much more than the idea that all matter is essentially discrete and ultimately composed of particles which are identical or nearly identical; but Dalton's hypothesis is something quite different; and, in order to make his procedure clear, one must review two or three, at least, of the facts which had been clearly established before his time.

(i) It had been observed by T. O. Bergman (1735–1784), by A. L. Lavoisier (1743–1794) and others that metallic copper when immersed in a neutral solution of silver nitrate goes into solution while the silver is displaced and appears in metallic form, *always keeping the solution neutral.* Lavoisier interpreted this to mean that these two quantities of silver and copper are simply the respective quantities which will unite with one and the same quantity of oxygen—the "acid-producer." One has here a distinct approach to the law of definite proportions without any suggestion whatever of the atomic theory.

There was another school of chemists, however, headed by C. L. Berthollet (1748–1822), who insisted that no sharp distinction can be drawn between chemical compounds, alloys, and solutions; but, largely through the efforts of another Frenchman, J. L. Proust (1755–1826), the variability of chemical composition was proved to be false; for Proust showed that in every case where Berthollet thought he had a substance of variable composition he really had mixtures, in different proportions, of certain compounds each of which had a definite and fixed composition.

By the year 1806, it was on every side recognized that Proust was correct and that he had established, without any reference to the atomic constitution of matter, what we now call the law of definite proportions.

(ii) A second fundamental discovery antedating the atomic theory is that of J. B. Richter (1762–1807), a German mineralogist, who showed that if we know the proportions in which the elements combine with any one of their number we know also the proportions in which they combine with each other. If B is the amount of a simple substance which unites with a given quantity, A, of another element to form AB; and if C is the weight of a third substance combining with A to form AC; then the weights of B and C, when they unite with each other to form the substance BC, are unchanged. This generalization is known as the law of reciprocal proportions.

Here are two separate experimental facts. Dalton or anyone else might have explained both of them very simply in terms of an atomic theory and might have insisted upon them as cogent evidence for the correctness of such a theory. It is one of the curiosities of history, however, that Dalton did *not* arrive at his atomic hypothesis by this route. Some of Dalton's own manuscript laboratory notes were discovered in the rooms of the Manchester Literary and Philosophical Society by Roscoe and Harden and were published by these men, in 1896, in a volume entitled *A New View of the Origin of Dalton's Atomic Theory*. These notes make it clear that Dalton's previous study of the atmosphere and other gases led him to the atomic structure of matter as a purely physical conception. He had arrived at the law of multiple proportions as early as the year 1802: but oddly enough he does not build upon this. Everything that Dalton writes indicates that he was thinking along the line of Newton's chapter on elastic fluids,[6] and that he was firmly convinced that the particles of any one gas differ in size and weight from those of any other gas. It is not, therefore, entirely surprising that he should reach the atomic theory in a deductive way. A paragraph or two from Dalton's great book, *A New System of Chemical Philosophy* (1808) will help to clarify the situation:

> "There are three distinctions in the kinds of bodies, or three states, which have more especially claimed the attention of philosophical chemists; namely, those which are marked by the terms *elastic fluids, liquids, and solids*. A very famous instance is exhibited to us in water, of a body, which, in certain circumstances, is capable of assuming all the three states. In steam we recognise a perfectly elastic fluid; in water, a perfect liquid; and in ice, a complete solid. These observations have tacitly led to the conclusion which seems universally adopted, that all bodies of sensible magnitude, whether liquid or solid, are constituted of a vast number of extremely small particles, or atoms of matter bound together by a force of attraction, which is more or less powerful according to circumstances. * * *
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> "Whether the ultimate particles of a body, such as water, are all alike, that is, of the same figure, weight, &c. is a question of some importance. From what is known, we have no reason to apprehend a diversity in these particulars: if it does exist in water, it must equally exist in the elements constituting water, namely, hydrogen and oxygen. Now it is scarcely possible to conceive how the aggregates of dissimilar particles should be so uniformly the same.
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> * * * * *
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> "When any body exists in the elastic state, its ultimate particles are separated from each other to a much greater distance than in any

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[6] *Principia*, Book II, Chapter V.

other state; each particle occupies the centre of a comparatively large sphere, and supports its dignity by keeping all the rest, which by their gravity, or otherwise, are disposed to encroach upon it, at a respectful distance. When we attempt to conceive the *number* of particles in an atmosphere, it is somewhat like attempting to conceive the number of stars in the universe: we are confounded with the thought. But if we limit the subject, by taking a given volume of any gas, we seem persuaded that, let the divisions be ever so minute, the number of particles must be finite; just as in a given space of the universe, the number of stars and planets cannot be infinite.

"Chemical analysis and synthesis go no farther than to the separation of particles one from another, and to their reunion. No new creation or destruction of matter is within the reach of chemical agency. We might as well attempt to introduce a new planet into the solar system, or to annihilate one already in existence, as to create or destroy a particle of hydrogen. All the changes we can produce, consist in separating particles that are in a state of cohesion or combination, and joining those that were previously at a distance."

The following paragraph taken from his syllabus of a lecture given in 1810 one year before the announcement of Avogadro's law shows more exactly how Dalton was led from the preceding considerations to the definite conception of atomic weights.

"The different *sizes* of the particles of elastic fluids under like circumstances of temperature and pressure being once established, it became an object to determine the relative *sizes* and *weights*, together with the relative *number*, of atoms in a given volume. This led the way to the combinations of gases, and to the number of atoms entering into such combinations the particulars of which will be detailed more at large in the sequel. Other bodies besides elastic fluids—namely, liquids and solids—were subject to investigation, in consequence of their combining with elastic fluids. Thus a train of investigation was laid for determining the *number* and *weight* of all chemical elementary principles which enter into any sort of combination one with another."

It is evident, Dalton says, that since *one* measure of nitrogen unites with *one* measure of oxygen to form two measures of nitrous gas that these two volumes of nitrous gas could not have more particles than had one measure of oxygen or of nitrogen. Hence he concludes that the atoms of each gas are different in size from those of any other and that in virtue of this fact they are able to diffuse. This conclusion Dalton appears to derive from the completeness of diffusion and combination and from the homogeneity of the product. Knowing the densities of these various gases, he thought it a mere mechanical problem to find also the relative weights of the particles going to make up a gas and hence to find the relative volumes of the particles.

Dalton was acquainted with a number of substances composed of only two elements; among these were marsh gas (CH_4), ethylene (C_2H_4), water (H_2O), carbon dioxide (CO_2), and ammonia (NH_3). It was clear to him that he might select any element as a standard and assign to it an arbitrary weight of unity; but how was he to determine how many atoms of another element combine with it to form the particular compound under consideration. The assumption which he made was the simplest possible, namely, *whenever two elements unite in a single proportion, it may be assumed that the product is a combination of one atom of each; and when two combinations are observed, he assumes one to be a binary and the other a ternary.* Upon this basis, he proceeded to determine a series of molecular weights; and from these molecular weights a series of atomic weights in terms of hydrogen as unity.

It is easy enough for one of the present generation to feel that, all through Dalton's reasoning, the one missing link is Avogadro's law. The one serious objection, indeed, that was raised against the atomic theory at the time of its enunciation was that it rested upon no rational basis. Its foundation was represented as *a mere assumption* regarding the number of atoms of an element which go into combination with an atom of another element. Only three years elapsed, however, between the appearance of Dalton's *New System* and the removal of this objection by a well known Italian, Amedeo Avogadro (1776–1856), who taught higher physics for many years at the University of Turin. The law which goes by his name was enunciated by him in 1811.

One enthusiastic adherent of the atomic theory, Dr. Prout of England, having observed that many atomic masses are whole numbers, went so far as to make the hypothesis, in 1815, that all elements are made up of hydrogen atoms—the protyle of the ancients. How this view was overthrown by the accurate measures of Stas and how it has been reestablished, in a modified form, by the recent work of Thomson, Rutherford, Aston, and Dempster forms one of the most fascinating and illuminating chapters in modern science.

Well within the first quarter of the nineteenth century, the two essential features of Dalton's theory were almost everywhere recognized and accepted. These features are as follows:

(i) Each chemical element is made up of similar atoms of constant weight.

(ii) Each chemical compound is formed by the union of atoms of different elements in some simple numerical ratio.

Even this brief sketch of the rise of the atomic theory must not close without a word about the training of this Quaker school teacher who first succeeded in taking the ideas of Democritus and Newton and so transforming them and developing them that they are now able to give us a quantitative account not only of the composition of all substances but also of the manner in which these substances react one upon another.

Dalton was a lad of ten summers when the Declaration of Independence was signed. He died at Manchester, England, in 1844. An autobiographical note which he once wrote will give the facts and at the same time serve to illustrate his simple style.

> "The writer of this was born at the Village of Eaglefield about two miles west of Cockermouth, Cumberland. Attended the village school there & in the neighborhood till 11 years of age, at which period he had gone through a course of Mensuration, Surveying, Navigation, &c., began about 12 to teach the Village School & continued 2 years afterwards; was occasionally employed in husbandry for a year or more; removed to Kendal at 15 years of age as assistant in a boarding School, remained in that capacity for 3 or 4 years, then undertook the same School as a principal & continued it for 8 years, & while at Kendal employed his leisure in studying Latin, Greek, French & the Mathematics with Natural Philosophy, removed thence to Manchester in 1793, as Tutor in Mathematics & Natural Philosophy in the New College, was 6 years in that Engagement, & afterwards was employed as private & sometimes public Instructor in various branches of Mathematics, Natural Philosophy & Chemistry chiefly in Manchester, but occasionally by invitation in other places, namely London, Edinburgh, Glasgow, Birmingham & Leeds."

Such is the modest account which Dalton gives of his own training and life-work.

The theory of Avogadro, that equal volumes of gases contain equal numbers of molecules, received a much more tardy acceptance than did the theory of Dalton. The symbol for water was still widely written HO, instead H_2O, up to and even after the middle of the nineteenth century. This means, of course, a failure to recognize the fundamental distinction which Avogadro had pointed out between the *molecule* and the *atom* of any particular gas. The complete acceptance of the atomic theory, as modified by Avogadro, is perhaps fairly well indicated, in America at least, by the appearance of such a volume as *The New Chemistry* by Professor J. P. Cooke which was published as one of the International Scientific Series in 1873. The following paragraph from Mendeleeff's Faraday Lecture given at the Royal Institution in London, 4 June 1889, will serve to indicate the feeling in Europe as late as 1860.

> "Reverting to the epoch terminating with the sixties, it is proper to indicate three series of data without the knowledge of which the periodic law could not have been discovered, and which rendered its appearance natural and intelligible.
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> "In the first place, it was at that time that the numerical value of atomic weights became definitely known. Ten years earlier such knowledge did not exist, as may be gathered from the fact that in 1860 chemists from all parts of the world met at Karlsruhe in order to come to some agreement, if not with respect to views relating to atoms, at any rate as regards their definite representation. Many of those present probably remember how vain were the hopes of coming to an understanding, and how much ground was gained at that congress by the followers of the unitary theory so brilliantly represented by Cannizaro. I vividly remember the impression produced by his speeches, which admitted of no compromise, and seemed to advocate truth itself, based on the conceptions of Avogadro, Gerhardt, and Regnault, which at that time were far from being

generally recognised. And though no understanding could be arrived at, yet the objects of the meeting were attained, for the ideas of Cannizaro proved, after a few years, to be the only ones which could stand criticism, and which represented an atom as—'the smallest portion of an element which enters into a molecule of its compound.' Only such real atomic weights—not conventional ones—could afford a basis for generalisation. It is sufficient, by way of example, to indicate the following cases in which the relation is seen at once and is perfectly clear:

K = 39 Rb = 85 Cs = 133
Ca = 40 Sr = 87 Ba = 137

whereas with the equivalents then in use—

K = 39 Rb = 85 Cs = 133
Ca = 20 Sr = 43.5 Ba = 68.5

the consecutiveness of change in atomic weights, which with the true values is so evident, completely disappears."

CHAPTER X

From Volta to Oersted

"Rejoice, O young man in thy youth."
—*Ecclesiastes*, xi, 9.

In an earlier chapter, "Pioneers of Electrical Science," we have traced the history of the amber phenomenon up to the time when Volta announced the discovery of his cell to the Royal Society of London through a letter to its president, Sir Joseph Banks, written from Como on March 20, 1800. It will be generally conceded that the next electrical discovery of the first rank is the one which H. C. Oersted made known to some of his friends under date of Copenhagen, June 21, 1820. No greater mistake could be made, however, than to imagine that the two decades which intervene between these discoveries were periods of stagnation. In Mottelay's great *Bibliographical History of Electricity and Magnetism*, no less than 150 octavo pages are devoted to these twenty years. Volta, in his well known letter to the Royal Society, points out very clearly that his new electric column is more closely akin to the electric eel than to the Leyden jar, since the electric pile is always ready to give a shock while the Leyden jar loses this ability the instant it is discharged. In one paragraph Volta speaks of his cells as constituting an *organe électrique artificiel;* in another place he speaks of my *appareil électro-moteur;* and, near the close of the letter, he maintains that galvanism consists in a "circulation sans fin du fluide électrique, dans un cercle de conducteurs." These very modern views of Volta did not, however, receive immediate acceptance at the hands of French and English men of science. Some considered the identity of electricity and galvanism (as static and current electricities were then known), to be proved only when Dr. W. H. Wollaston (1766–1828) succeeded in decomposing water by the sparks of a frictional electric machine in the same manner as had already been done by the use of voltaic cells. Later generations, perhaps, were not thoroughly convinced of this identity until H. A. Rowland (1848–1901) showed, in his Berlin experiment of 1876, that an electrostatic charge when put into motion produces a magnetic field similar to that of a Voltaic current.

At the very beginning of the nineteenth century, there were only two modes of estimating electrical effects; one was that of physiological shock, the other that of the gold leaf electrometer. These entirely inadequate means for making any quantitative study of electrical phenomena left the subject much in the position in which psychology and other social sciences are today. Under these circumstances, much prominence was given to "animal electricity;" numerous reports of the medicinal effects of the electric current are to be found in serious-minded journals of the period, such as the *Philosophical Magazine*. Thus in volume 12, page 105, of the periodical just mentioned, there is reported a remarkable cure accomplished by use of a galvanic belt consisting of fifteen small square plates of zinc, each connected by two links of plated copper wire, the two ends being fastened by a common hook-and-eye. Again in the same volume, page 374, is a report from Cassel in Germany of many successful cures of the lame, deaf and blind by a few weeks use of the Voltaic pile.

All this is, of course, vastly more excusable than the numerous advertisements of "electric hair brushes" and "galvanic belts" to which our daily press gave space at the latter end of this same century. In these early years, men were feeling their way through the many new and unknown properties of an invisible agent; but those who, at the other end of the nineteenth century, advertise a compound—generally known as water—under the caption "88 per cent oxygen" and sell it as having therapeutic value, simply illustrate the well known fact that of all the mean forms of lying the meanest is that in which the would-be-deceiver speaks only the literal truth.

ELECTROLYSIS

One of the first steps out of this haze, which surrounded electrical science at the beginning of the century, was the discovery by two Englishmen, Nicholson and Carlisle,[1] of that electro-chemical effect now known as the electrolysis of water. The observation of these men that, when the "galvanic circle" is closed by means of a drop of water, small bubbles of hydrogen gas are given off from the terminal connected with the zinc plate, opened up a new and large field of chemistry which was at once vigorously cultivated by Sir Humphry Davy. The scientific periodicals of the time are filled with papers describing new

[1] *Philosophical Magazine*, (series 1), 7, pp. 338–347, 1800.

forms of the voltaic cell. Of all these discussions those of Davy and Grotthuss are perhaps the most important, since they go far toward establishing a chemical theory of the cell. Davy shows that a cell does not require two different metals; that one metal and two fluids will suffice, provided one of the fluids will oxidize the metal.

C. J. D. Grotthuss (1785–1822), a Prussian, printed at Rome in 1805,[2] when he was only twenty years of age, a theory of electrolysis which has served as a foundation upon which nearly all subsequent theories have been built. The essential features of his viewpoint are contained in the following paragraphs:

[illegible]

> "XV The decomposition of water by the electrometer apparatus has for a long time exercised the ingenuity of chemists and naturalists, to whom this phaenomenon affords a delicate problem to resolve in order to reconcile it with the theory of the nature of water. It is first necessary to know if the two products of the two Galvanic poles come from one and the same molecule of water, or rather from two different molecules; and in the latter case we may ask what becomes of the hydrogen at the place where oxygen only is perceived? and in return, what becomes of the oxygen where hydrogen only is perceived?
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> "XVI The column of Volta, which will immortalize his name, is an electrical magnet, every element of which (*i.e.* each pair of disks) possesses its negative and positive pole. The consideration of this polarity suggested to me the idea that it might establish a similar polarity among the elementary molecules of the water solicited by the same electrical agent; and I confess that this afforded me a spark of light on the subject.
>
> "XVII Let us suppose, therefore, that at the moment of the generation of the hydrogen and the oxygen, there takes place in these

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[2] Grotthuss' paper is translated and reprinted in the *Philosophical Magazine*, (series 1) 25, pp. 330–339, 1806.

two bodies, as well by contact as by the friction of the one against the other, a separation of their natural electricity in such a manner that the former acquires the positive and the latter the negative state; it follows, that the pole from which the resinous electricity continually flows will attract the hydrogen by rejecting the oxygen, whereas the pole animated with the vitreous electricity will attract the oxygen by rejecting the hydrogen.[3] Thus, when the Galvanic current traverses a quantity of water, each of the two component principles of the latter is solicited by an attractive force and by a repulsive force, of which the centres of action are reciprocally opposite, and which, by acting in the same manner, determines the decomposition of this liquid."

Davy's point of view is set forth in his first Bakerian Lecture of which the following paragraph is typical:

"It will be a general expression of the facts that have been detailed, relating to the changes and transitions by electricity, in common philosophical language, to say that hydrogen, the alkaline substances, the metals, and certain metallic oxides, are attracted by negatively electrified metallic surfaces, and repelled by positively electrified metallic surfaces; and contrariwise, that oxygen and acid substances are attracted by positively electrified metallic surfaces, and repelled by negatively electrified metallic surfaces; and these attractive and repulsive forces are sufficiently energetic to destroy or suspend the usual operation of elective affinity.

"It is very natural to suppose that the repellent and attractive energies are communicated from one particle to another particle of the same kind, so as to establish a conducting chain in the fluid; and that the locomotion takes place in consequence; and that this is really the case seems to be shown by many facts."[4]

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[3] Considering the diversity of substances deposited at the negative pole, it would be more simple, and perhaps more just, to admit only an attractive and repulsive force acting upon the oxygen, without attributing it to the poles in relation to the hydrogen.

[4] *Philosophical Magazine*, (series 1), 28, p. 111, 1807.

Quite independently of Grotthuss and Davy, the germ of electroplating had already been discovered by Brugnatelli, a colleague of Volta's at the University of Pavia, in 1802. Early in the same year, J. W. Ritter (1776–1810) in Bavaria had succeeded in charging a secondary electric pile built up of discs of *one* metal separated by pieces of moistened cloth, thus blazing a path toward the modern storage cell.

Electrolysis also gave to the laboratory a new current measuring instrument. Joseph Izarn (1766–1834), a French professor of physics, in his *Manuel du Galvanisme* (Paris, 1805), introduces his chapter on galvanometers with the following remark:

> "Je ne connais que trois moyens employés jusqu'ici pour apprécier les effets galvaniques. Le premier et le plus fréquemment mis en usage, est celui des commotions et de la saveur; le second est fondé sur l'action, à distance, des extrémités de l'Electromoteur sur les corps légers; et le troisième, sur les effets résultans de la décomposition de l'eau."

The form which the electrolytic galvanometer took at this time is quite sufficient to explain why it never came into general use. The instrument consisted of a straight graduated glass tube, provided with metal terminals at each end, and partially filled with an electrolyte. Such a device did not, of course, indicate the instantaneous value of the current but gave only the time-integral of the current; not only so, but it had, in general, such high resistance that when placed in any circuit it would immediately and seriously diminish the current which it was desired to measure.

Of all work done during these two decades, the most outstanding is doubtless the isolation of potassium and sodium in 1807 by Davy. He availed himself of a powerful voltaic battery, consisting of 250 large cells, to pass an electric current through "a piece of pure potash which had been exposed for a few seconds to the atmosphere to give conducting power to the surface." Davy says:

> "Under these circumstances a vivid action was soon observed to take place. The potash began to fuse at both its points of electrization. There was a violent effervescence at the upper surface; at the lower or negative surface, there was no liberation of elastic fluid; but small globules having a high metallic lustre, and being exactly similar in visible characters to quicksilver, appeared, some of which burnt with explosion and bright flame, as soon as they were formed, and others remained, and were merely tarnished, and finally covered by a white film which formed on their surfaces."

By the end of another year, Davy had isolated barium, calcium, and strontium. His greatest service lay, perhaps, in showing that it is calcium rather than lime, potassium rather than potash, and sodium rather than soda, which are the really elementary substances.

The quantitative laws of electrolysis curiously enough were not enunciated until a generation later when in 1833 Faraday[5] proved that the mass of any particular kind of ion set free by a current is proportional to the whole quantity of electricity which passes and to the electro-chemical equivalent of the ion. The electro-chemical equivalent he had already defined as being proportional to the chemical equivalent.

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[5] *Experimental Researches*, §§ 366 and 377.

The heating effect of an electric current had long been known and was studied by Davy in London and by Dr. Robert Hare in Philadelphia; but it remained for J. P. Joule (1818–1889) to describe this effect quantitatively in 1840.[6] The long interval of time—a third of a century—between the invention of the voltaic cell and the discovery of the laws which control the electrolytic and thermal effects of the current is mainly due to the want of any convenient and reliable galvanometer.

Some curious effects of ionization were also observed at this period; for example, the fact that a candle flame placed between two plates, one charged positively, the other negatively (either by use of voltaic cells or by means of an electric machine) is always attracted toward the negative plate was reported to the Royal Society in 1814 by W. T. Brande,[7] the successor of Sir Humphry Davy at the Royal Institution. The explanation of this fact came only at the very end of the nineteenth century when in the Cavendish Laboratory at Cambridge, it was demonstrated that the mobility of the electrons freed by the flame is far greater than that of the positive ions. The result of the electrons leaving the flame is what Davy called "unipolarity" and what we today study under the head of "unilateral conductivity." This is, of course, a phenomenon quite different from that known as "the electric wind" or the little whirl illustrating the reaction from a point discharge.

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[6] *Philosophical Magazine*, 19, p. 260, 1841.

[7] Reprinted in the *Philosophical Magazine*, (series 1), 44, p. 124, 1814.

DAVY AND FARADAY

In October of 1813, Sir Humphry Davy and his wife made a tour of continental Europe which is not without interest for the history of science. It will be noted that he started on the trip only two years before the close of the Napoleonic wars, spent two winters abroad and did not return until the year of Waterloo. Before leaving London, he had obtained the permission of Napoleon to travel in France; but once having reached Paris he was the recipient of many honors and was even elected to honorary membership in the Institut National which, for twenty years following the French Revolution, took the place of the Académie des Sciences.

Davy was the guest of the leading scientific men of France and Italy and was often accorded the facilities of their laboratories for his own experimental investigation. At the present time any such exchange of courtesies between two countries at war is obviously impossible; science no longer ranks, in the estimation of governments or in popular judgment, as merely an intellectual sport. Any investigator in physical science as able and skillful as Davy and coming from the enemy country would today have the utmost difficulty in crossing the frontier, and would be more likely to have his name stricken from the rolls of a national academy than to be placed on the honor list. Such a tool has science become in the hands of the men who wage war!

On this trip Davy took with him as assistant and secretary the young Faraday, then only twenty-two years of age. For the bookbinder's apprentice, the trip was, of

From a painting by W. Hunt

The Royal Institution at London

The young Faraday assisting Sir Humphry Davy

course, a liberal education. Here he made the personal acquaintance of such men as Ampère and Volta; he saw the inside working of the best laboratories of Paris, Florence, and Rome; and it is safe to say that no traveller ever crossed Europe with a mind more alert and receptive than Faraday's. Little wonder it is that Sir Humphry Davy when asked to name his most important discovery should have made that well known reply, "Michael Faraday!"

It was some six months before starting upon this journey that Faraday had come to the Royal Institution in the capacity of laboratory assistant. A fascinating picture of the two men at this period has been painted by W. Hunt and engraved by J. G. Murray. The scene is the laboratory at the Royal Institution, 22 Albemarle Street, London. Retorts, furnaces, bellows, shovels, brooms and other implements are scattered about the room. Davy in knee breeches is working over a large crucible; Faraday, wearing a long apron, stands at a sink in the corner intently engaged in cleaning some chemical apparatus. A copy of this engraving hangs just inside the entrance of the Chemists' Club on Forty-first Street, New York and it has been happily reproduced by Dr. A. S. Cushman in his *Chemistry and Civilization.* Davy was not only lacking in self-control but he was also deficient in the sense of order. This latter is well illustrated in the picture and makes it easy to understand Faraday's remark that "the greatest of all his great advantages was that he had a model to teach him what he should avoid."[8]

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[8] Bence Jones, *Life and Letters of Faraday*, vol. 1, p. 210, London, 1870.

It must not be inferred from this remark, however, that Faraday failed to appreciate the great merits of his predecessor; on the contrary, indeed, his praise of Davy was sincere and unstinted.

THOMAS YOUNG—A REVIEW

The years between 1810 and 1820, the second of the two decades we have been following, was a period of comparative barrenness, marked by no electrical contribution of first, or even second, rank. With 1820, the early history of electricity and magnetism closes and a new era begins. As we leave this period, standing at the opening of the nineteenth century, it will be worth while to glance back over the eighteenth and compare the status of electrical science at the beginnings of these two centuries. This can best be done, perhaps, by considering two of the most famous treatises on physics ever written. The first is that of the Frenchman, Jacques Rohault (1620–1675) whose *System of Natural Philosophy*, was translated from French into Latin for use on the continent, and into English for use in Great Britain. The second edition appeared in London about the time of Newton's death; it represents the best physics of the day and covers more than six hundred octavo pages; yet nowhere in the index of these two large volumes, which had a long and wide circulation, does one find any entry under either *electricity* or *magnetism*. For the former of these one must turn to *amber;* for the latter, to *lodestone.* The chapter devoted to lodestone covers twenty-five modest pages and includes, at the very end, a treatment of the amber phenomena occupying less than two pages. Here it is obvious that one can find only the simplest facts of electrostatics. The subjects which bulk large are kinematics, mechanics, optics, cosmography, meteorology and the physiology of the human body.

Turning now to the other great treatise, Thomas Young's *Lectures on Natural Philosophy and the Mechanical Arts* (two volumes, London, 1807), one finds, after the lapse of a century, three lectures under the following captions "LIII. On Electricity in Equilibrium," "LIV. On Electricity in Motion," "LV. On Magnetism," altogether covering fifty-eight, out of a total of fifteen hundred, pages. Here are given the very latest results of Volta, Davy, and others together with some reflections upon the state of the science which fairly represent the contemporary thought of the period. The treatment, it will be observed, is still exceedingly meagre. The following paragraphs are typical.

> "It must be confessed that the whole science of electricity is yet in a very imperfect state; we know little or nothing of the intimate nature of the substances and actions concerned in it; and we can never foresee, without previous experiment, where or how it will be excited. We are wholly ignorant of the constitution of bodies, by which they become possessed of different conducting powers; and we have only been able to draw some general conclusions respecting the distribution and equilibrium of the supposed electric fluid, from the laws of the attractions and repulsions that it appears to exert. There seems to be some reason to suspect, from the phenomena of cohesion and repulsion, that the pressure of an elastic medium is concerned in the origin of these forces; and if such a medium really exists, it is perhaps nearly related to the electric fluid. The identity of the general causes of electrical and of galvanic effects is now doubted by few; and in this country the principal phenomena of galvanism are universally considered as depending on chemical changes; perhaps,

also, time may show, that electricity is very materially concerned in the essential properties, which distinguish the different kinds of natural bodies, as well as in those minute mechanical actions and affections which are probably the foundation of all chemical operations; but at present it is scarcely safe to hazard a conjecture on a subject so obscure, although Mr. Davy's experiments have already in some measure justified the boldness of the suggestion.

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"There is no reason to imagine any immediate connection between magnetism and electricity, except that electricity affects the conducting powers of iron or steel for magnetism, in the same manner as heat or agitation. In some cases a blow, an increase of temperature, or a shock of electricity, may expedite a little the acquisition of polarity; but more commonly any one of these causes impairs the magnetic power.

* * * * *

"In subjects so little understood as the theory of magnetism, we are obliged to admit some paradoxical propositions, which are only surprising on account of the imperfect state of our knowledge. Yet, little as we can understand the intimate nature of magnetical actions, they exhibit to us a number of extremely amusing as well as interesting phenomena; and the principles of crystallization, and even of vital growth and reproduction, are nowhere so closely imitated, as in the arrangement of the small particles of iron in the neighbourhood of a magnet, and in the production of a multitude of complete magnets, from the influence of a parent of the same kind."[9]

No serious minded student of physics will fail to make the acquaintance of Dr. Thomas Young; for he is the last man, unless one includes Whewell and Helmholtz, of the race that knew everything that was to be known, the group that includes Aristotle, Leonardo da Vinci, Stevin, Galileo, Descartes, Huygens, Franklin.

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[9] *Lectures on Natural Philosophy*, vol. I, pp. 683–695.

Young was born of a well-to-do Quaker family at Milverton, England in 1773 and died at London fifty-six years later. His education, in respect to the amount of ground it covered, is quite as remarkable as his later scientific work. As a lad he showed marked proficiency in linguistic studies, acquired great mechanical skill, distinguished himself in drawing, music, and athletics. As a young man he pursued his university studies at London, Edinburgh, Göttingen, and Cambridge.

He inherited ample money; he had all that travel, leisure, and good society could do for a man. Only in one particular does his education appear to have been defective, viz., in the absence of any training in advanced dynamics or in higher mathematical analysis.

In 1800 he completed his medical studies at Cambridge, and settled as a practising physician in London. In the year following he was appointed to the professorship of natural philosophy in the then newly founded Royal Institution, a position from which he resigned at the end of two years in order to devote himself more completely to the practice of medicine. It was during his occupancy of this chair that he wrote his *Lectures on Natural Philosophy*, which must always be reckoned as a potent factor in the spread of sound physical science in the nineteenth century, while its bibliography of more than four hundred quarto pages is today valuable as well as classic.

But nothing short of a catalogue of his papers can give one an adequate idea of the varied activity of this man during the remaining quarter-century of his life. His contributions cover fields as diverse as the physiology of the human eye, hydrodynamics, music, paleography, atmospheric refraction, theory of tides, tables of mortality, theory of structures. His explanation of color-vision as due to the presence of three sets of nerve fibers in the retina, which, when excited, give respectively sensations of red, green, and violet, has been adopted and modified by Helmholtz; and is today perhaps the most widely accepted, if not the best, of the various theories on this subject.

After all, it must be confessed, even by his most ardent admirers, that Young's style is, in general, far from clear. Whether this is in any way connected with his lack of mathematical training, or whether it is due to the fact that his own clear intuitions bridged most of the gaps in his written work, it is difficult to say; but in any event many of his papers are obscure, and few of them are read. The reader who desires a full biography will find it in Dr. Peacock's *Life of Young* (London, 1855). This biographer also edited his *Miscellaneous Works*, (three volumes, London, 1855). All his papers, however, which are of especial interest to the student of physics are contained in the *Lectures on Natural Philosophy.*

Summarizing the period of 1800–1820, the period of the retreat from Moscow, the battle of Waterloo and the Congress of Vienna, the period of Fresnel, Fraunhofer, Dalton, and Berzelius, one can say that it was not a time of revolutionary ideas in electrical science. These were years of steady growth. The outstanding event is perhaps the creation of the science of electro-chemistry. J. J. Berzelius (1779–1848) added much to the work of Davy and among other things introduced the modern system of chemical nomenclature, replacing the geometric signs of Dalton by the initial letters of the Latin names of the elements. His electro-chemical theory will be found in his memoir of 1814 on *The Theory of Chemical Proportions and Chemical Action of Electricity.*

CHAPTER XI

ELECTROMAGNETISM

"Majores vestros et posteros cogitate."
—TACITUS, *Agricola*, 32.

The modern era of electrical science was initiated by two outstanding discoveries separated by a period of eleven years. Of these the first was announced by H. C. Oersted (1777–1851) on July 21, 1820; the second, by M. Faraday (1791–1867) on November 24, 1831. Together they form the foundation of the science of electromagnetism which includes practically all modern applications of electricity such as telegraphy, telephony, dynamoelectric machinery, and radio communication. It is the purpose of this chapter to trace these two great principles through their various formulations and consequences up to their appearance in recent inventions.

OERSTED'S DISCOVERY—THE FIRST LAW OF ELECTROMAGNETISM

The essential feature of Oersted's discovery is contained in the following sentences from his Latin circular as translated in Thomson's *Annals of Philosophy* for October, 1820:

> "The opposite ends of the Galvanic battery were joined by a metallic wire, which, for shortness sake, we shall call the *uniting conductor*, or the *uniting wire*. To the effect which takes place in this conductor, and in the surrounding space, we shall give the name of the *Conflict of Electricity*.

> "Let the straight part of this wire be placed horizontally above the magnetic needle, properly suspended, and parallel to it. If necessary, the uniting wire is bent so as to assume a proper position for the experiment. Things being in this state, the needle will be moved, and the end of it next the negative side of the battery will go westward."

It must not be imagined that Oersted had no predecessor; for both Father Beccaria (1716–1781) and J. W. Ritter (1776–1810) had written and experimented along this line; but the demonstration of Oersted was the first clear and definite evidence for thinking that a magnetic field surrounds every wire conveying an electric current. He gave no quantitative description of the phenomenon; but he did point out that the magnetic effect is "dispersed pretty widely in the circumjacent space."

Among the many results announced in this brief Latin circular of Oersted's, the two following were full of surprise to his contemporaries; that the magnetic field is perpendicular to the plane which contains the wire and the magnet pole, and that the effect is just the same whatever the material of the wire conveying the current.

Oersted pursued science vigorously but not passionately. His tastes were wide with a strong leaning to literature and history. The circumstances of the discovery are given, as follows, by one of his most distinguished listeners, Christopher Hansteen (1784–1873) in a letter to Faraday under date of Christiania, December 30, 1857, as follows:

> "Professor Oersted was a man of genius, but he was a very unhappy experimenter; he could not manipulate instruments. He must always have an assistant, or one of his auditors who had easy hands,

to arrange the experiment; I have often in this way assisted him as his auditor. Already in the former century there was a general thought that there was a great conformity, and perhaps identity, between the electrical and magnetical force; it was only the question how to demonstrate it by experiments. Oersted tried to place the wire of his galvanic battery perpendicular (at right angles) over the magnetic needle, but remarked no sensible motion. Once, after the end of his lecture, as he had used a strong galvanic battery to other experiments, he said, 'Let us now once, as the battery is in activity, try to place the wire parallel with the needle;' as this was made, he was quite struck with perplexity by seeing the needle making a great oscillation (almost at right angles with the magnetic meridian). Then he said, 'Let us now invert the direction of the current,' and the needle deviated in the contrary direction. Thus the great detection was made; and it has been said, not without reason, that 'he tumbled over it by accident.' He had not before any more idea than any other person that the force should be *transversal*. But as Lagrange has said of Newton in a similar occasion, 'such accidents only meet persons who deserve them.'"[1]

AMPERE AND THE MAGNETIC SHELL

This new property of an electric current was reported to the French Academy by Arago on September 11, 1820. At the very next session, September 18, A. M. Ampère (1775–1836) showed that a "galvanic spiral" acted as a magnet and that all magnetic phenomena may be reduced "to effects purely electric." At the meeting in the following week, September 25, Ampère announced the new fact of "the attraction and repulsion of two electric currents without the intermediation of any magnet."[2] In taking this step, Ampère laid the foundation of the

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[1] Bence Jones, *Life of Faraday*, vol. II, p. 395.

[2] Philosophical Magazine, (series 1), 57, p. 47, 1821.

Jean Baptiste Biot (1774–1862)

A member of that brilliant group of French physicists which flourished in the first quarter of the nineteenth century

science of electrodynamics; but during the next four years he erected upon this foundation one of the most celebrated structures of physical theory, the essential feature of which is that the ponderomotive force acting upon an element of current ds in any magnetic field H is $i[ds \cdot H]$ where i is the current strength, H the field strength, and where the square brackets denote a vector product. This great paper of Ampère's which has rendered his name immortal and also made it a household word, has been reprinted by A. Hermann, Paris, 1883, under the original title of 1826, *Théorie mathématique des Phénomènes Électro-dynamiques uniquement déduite de l'Expérience.*

The intellectual activity of the French Academy at this period is well exemplified by the fact that within two months after the first announcement of the Oersted effect one of its members, working in conjunction with a young man shortly to become a member, discovered just how the magnetic field produced by a current flowing in a long straight wire varies with the distance from the wire. This discovery of J. B. Biot (1774–1862) and F. Savart (1791–1841) reported to the Academy on October 30, 1820, is most clearly described by writing $H = c\,i/r$ where i is the current strength, H the magnetic field at a perpendicular distance r from the wire, and c a proportionality constant which, in the c.g.s. system of units now employed by electric engineers, has the numerical value of "2".

Biot will always be remembered as one of the foremost physicists and astronomers of France. He helped Laplace correct the proof of the *Mécanique Céleste.* At the age of twenty-six, he was appointed to the chair of physics in the Collège de France and three years later was taken into the *Académie des Sciences.* Anyone who desires an authoritative and accurate picture of the science of physics at that period will find it in Biot's *Traité de physique expérimentale et mathématique* (Paris, 1816).

The upshot of Ampère's work was to establish at the very outset the equivalence between any electric circuit and a magnetic shell having the same boundary as the circuit, and having a definite magnetic moment for each unit area of the shell, namely a moment numerically equal to the strength of the current in the circuit which it replaces. Ampère's fiction of a magnetic shell has proven so helpful in clear thinking as to call for a word more in explanation.

Imagine a closed electric circuit; the bounding curve may be either plane or tortuous; suppose it to have the shape of a circle, an ellipse, a square, or any irregular shape. Next think of the space enclosed—a limited surface—as built up, after the fashion of a mosaic table-top, out of very short magnets, the north poles all headed one way, and having such strength that the magnetic moment of any unit area will be numerically equal to the current flowing in the boundary wire. This structure of the imagination is called a magnetic shell and produces, in the space outside of itself, all the effects of the electric current which it replaces.

The reader will be amply repaid by following, in greater detail than is here possible, the career of this remarkable man. His father, Jean-Jacques Ampère, was a retired merchant in Lyons at the outbreak of the French Revolution. He was one of a committee appointed by the city

L. Dymarie. aq f. et del. 1816

André Marie Ampère (1775–1836)
French physicist of the first order; creator of the science
of electrodynamics

to oppose the Terrorist government; and for the execution of this duty he paid the penalty of his life when the army of the National Convention captured the city. The superb spirit of this man is characterized as follows by Henry James in his essay on *The Two Ampères:*

> "In prison, before his death, he wrote his wife a letter, which we regret not having space to quote; it gives one a better opinion of human nature. 'Do not speak to Josephine,' he says at the end, 'of her father's misfortune; take good care that she does not know it; as for my son, there is nothing I do not expect from him. So long as you possess them and they possess you, embrace each other in memory of me. I leave my heart to all of you.' For so pure an old stoic as this to say on the edge of the scaffold that there was nothing he did not expect from his only son, left the sole support of two desolate women—this was a great deal."

The lad of eighteen after whom the International Congress of Electricians at Paris in 1881 named the unit of electric current was so heart-broken by this terrible event that he found no relief during his remaining years save that which came from work, with perhaps the exception of the few years of bliss which came into his life with Julie Carron, the lovely girl who became his wife in 1799, who bore him a distinguished son, Jean-Jacques Ampère, and who died in 1804. In 1809, the year of Lincoln's birth, Ampere received appointment as professor of mathematics in the École Polytechnique. Five years later, the Academy of Sciences at Paris elected him to membership. His beautiful character, his keen sensibilities and his catholicity of tastes are fully set forth in his *Journal et Correspondance* (Paris, 1872).

Contemporaneously with Ampère, a number of minor, yet exceedingly important, applications of Oersted's discovery were made. Arago showed (1820) that a bare metallic wire conveying an electric current would, if touched to a heap of iron filings, gather about itself many chains of magnetized iron particles. He also pointed out the magnetizing effect of a spiral conveying a current. William Sturgeon in 1825 did the same thing on a larger scale, showing that the iron core of a helix became a magnet hundreds of times stronger than the helix itself, so long as the current continued to flow.

SOME ELECTROMAGNETIC APPARATUS

J. S. C. Schweigger (1779–1857), Professor of physics and chemistry at Halle, in 1820, devised his multiplier which was merely a compass box with a coil of wire wrapped about it in the direction of the needle.[3] Here, of course, we have the germ of the modern galvanometer which is far and away the most sensitive instrument known for the detection of conduction currents. Hardly a single year in the nineteenth century has passed during which someone has not brought out some improvement in the galvanometer. All the beautiful ammeters and voltmeters, whether portable or for switchboards, which we owe to the labors of Nobili, Kelvin, D'Arsonval, Langley, Paschen, Weston, and others are based upon this fundamental discovery of Oersted.

On Christmas day of 1821, Faraday first succeeded in producing continuous mechanical motion by means of an electric current and a permanent magnet. The essential

[3] *Jour. f. Chemie u. Physik.*, 31, pp. 1–17, 1821.

feature of this discovery is that any portion of a conductor carrying an electric current, when placed in a magnetic field, always experiences a force tending to move itself in a direction at right angles both to the current and to the field. A couple of years later, in 1823, Peter Barlow modified this motor of Faraday's by mounting a wheel between the poles of a permanent magnet and passing a current from the axis to the periphery of the wheel always along a direction at right angles to the magnetic field. It is a long step from this simple "stellate wheel" of Barlow's to the modern electric motor in which currents and magnetic fields, each many thousands of times as strong, are employed; but there is no break in the continuity of the development and no new electromagnetic principle involved. For an account of Barlow's work, see William Sturgeon's *Scientific Researches* (Bury, 1850), p. 26.

We pass now to a brief digression on two minor discoveries, thermo-electricity and Ohm's law.

THE SEEBECK EFFECT

A totally new method of producing an electric current, one discovered by T. J. Seebeck (1770–1831) of Berlin, ought perhaps here to be mentioned for the sake of putting it in its proper chronological niche. Seebeck announced to the Berlin Academy, in 1822, that a ring formed of copper and bismuth, soldered together at the two junctions, will furnish an electric current as soon as one of these junctions is heated or cooled to a temperature different from that of the other. To prove this, one has only to place a compass needle inside the ring and in the plane of the ring. This novel phenomenon excited many hopes, which have never been realized, for the economical production of electric current directly from heat. The converse of the Seebeck effect was discovered by a French gentleman of leisure, J. C. Peltier (1785–1845) in 1834; and both discoveries were gathered into a general theory of thermo-electric phenomena, in 1851, by Lord Kelvin.[4] The usefulness of these thermoelectric currents in the measurement of temperature and in the detection of minute quantities of radiation has been powerfully developed in the hands of the Italian physicist, M. Melloni, and of two contemporary American physicists, A. H. Pfund and W. W. Coblentz. The sensibility of the modern thermo-couple has, indeed, reached the point where the radiation from a single candle at a distance of more than fifty miles can be detected, a delicacy which almost surpasses belief.

THE LAWS OF OHM AND KIRCHHOFF

It is reported that a lawyer once put the following question to Thomas A. Edison when the latter was on the witness stand: "Mr. Edison, what is Ohm's law?" To which Mr. Edison is said to have replied, "I do not know, Sir. Ohm's law contains essentially the whole of electrical engineering; and I am not familiar with the whole of that subject." There was much truth in what Mr. Edison said about Ohm's law; much more at the time he said it than now, in the first half of the twentieth century. Nevertheless the fundamental law which Ohm enunciated in 1826, and which he published in a separate memoir in the year following, must always be considered as an analogue of Fourier's law governing the flow of heat which was announced in 1822, some four years earlier. Not only so; even if one man had produced both these laws, they could hardly be comparable in importance with the two new and epoch-making facts of electromagnetism which we owe to Oersted and Faraday. What Ohm did was to quantify the already widely known fact that voltaic cells when joined in series give "intensity"; but when joined in parallel, give "quantity." That in doing this he consciously followed Fourier will be clear from the two following paragraphs from his memoir on *Die Galvanische Kette* (Berlin, 1827):

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[4] *Mathematical and Physical Papers*, 1, p. 316.

> "The magnitude of the transition between two adjacent particles, under otherwise exactly similar circumstances, I have assumed as being proportional to the difference of the electric forces existing in the two particles; just as, in the theory of heat, the transition of caloric between two particles is regarded as proportional to the difference of their temperatures.
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> * * * * *
>
> "The form and treatment of the differential equations thus obtained are so similar to those given for the propagation of heat by Fourier and Poisson, that even if there existed no other reasons, we might with perfect justice draw the conclusion that there exists an intimate connexion between both natural phaenomena; and this relation of identity increases, the further we pursue it."[5]

To thus reduce the flow of heat and the flow of electricity to one general principle was an achievement of high order; and is an example of the process of simplification which is always going on in the development of physics along with the opposite process, the multiplication of new facts ever tending toward greater complexity. Aside from the simplicity and wide applicability of Ohm's law, it proved itself, some years later, to have especial value as the defining equation for the quantity which Ohm called "reduced length" and which we now call "electrical resistance"; but this was, of course, not possible until both *current* and *E. M. F.* had received independent definitions, something which was not accomplished until about twenty years after the enunciation of Ohm's law.

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[5] Taylor, *Scientific Memoirs*, II, pp. 402–403.

In 1847, a brilliant young German of twenty-three, just graduating from the University of Königsberg, G. R. Kirchhoff, showed that Ohm's law carried with it two important corollaries which could be stated almost in words of one syllable and which put into our hands the power of telling just how any steady electric current divides up when it enters, not a single wire, but a net-work of conductors. The first of these corollaries refers to what happens at any point in the net-work where two or more conductors come together, and is as follows: *The algebraic sum of all the currents which meet at any point is zero.* The other law refers to any mesh in the net-work and reads as follows: *In any closed circuit, the algebraic sum of the products of the current and the resistance in each part of the circuit is equal to the E. M. F. in the circuit.* This paper of Kirchhoff's[6] may be looked upon as the completion of Ohm's work so far as steady currents in linear conductors are concerned. The corresponding problem for varying currents was solved by Maxwell and

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[6] *Poggendorff's Annalen*, 72, 1847.

Rayleigh nearly a generation later. In the year following (1848) Kirchhoff solved the problem of conduction in a three-dimensional body, using the powerful analogy which Fourier had already (1822) furnished to Ohm.

We shall again meet Kirchhoff in the history of spectroscopy, for it is to him that we owe much of the development of spectrum analysis, especially the complete theory of the method now employed for discovering the chemical constituents of the stars.

The law of conduction through gases is by no means so simple as that for metals; and this in spite of the fact that the process of conduction may be much simpler in gases than in metals. Gases conduct only when ionized by some means such as X-rays, ultraviolet light, or some radioactive element. The relation between the current and the potential gradient then becomes rather complex. The whole story has been told by Sir. J. J. Thomson.[7]

FARADAY'S DISCOVERY—SECOND LAW OF ELECTROMAGNETISM

The transformer has become such a popular toy with boys, the induction coil has been so widely used during the last two generations, and the whole process of producing a current in a coil of wire, by simply thrusting the end of a magnet into the coil, appears to us so simple that it is difficult to believe that two of the leading men of science, one on each side of the Atlantic, should have sought, through several years, to produce this phenomenon.

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[7] *The Conduction of Electricity Through Gases*, Cambridge University Press, 1903.

Such, however, is the fact. The possibility of obtaining an electric current by use of a magnet had occurred independently to Faraday in England and to Joseph Henry (1797–1878) in America. There is good reason for believing that Henry observed, as early as August 1830, that an instantaneous current is generated in a coil of wire whenever a magnetic field inside that coil is produced or changed. For the evidence, see the preface of Professor Joseph S. Ames' *Discovery of Induced Electric Currents*.[8] Faraday was, however, the first to publish his observations. He read a paper *On the Induction of Electric Currents* before the Royal Society of London on November 24, 1831. To him, therefore, by general consent, is due the credit of having discovered the second of the two fundamental phenomena of electromagnetism. Henry's paper appeared nearly a year later.[9]

The essence of the matter is contained in the two following paragraphs from Faraday's Royal Society paper:

"§2. Evolution of Electricity from Magnetism

"27. A welded ring was made of soft round bar-iron, the metal being seven-eighths of an inch in thickness, and the ring six inches in external diameter. Three helices were put round one part of this ring, each containing about twenty-four feet of copper wire one-twentieth of an inch thick; they were insulated from the iron and each other, and superposed in the manner before described (6), occupying about nine inches in length upon the ring. They could be used separately or conjointly; the group may be distinguished by the letter A (Pl. I. fig. 1). On the other part of the ring about sixty feet of similar copper wire in two pieces were applied in the same manner,

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[8] American Book Company, 1900.

[9] Silliman's *American Journal of Science*, 22, pp. 403–408, 1832.

> forming a helix B, which had the same common direction with the helices of A; but being separated from it at each extremity by about half an inch of the uncovered iron.
>
> "28. The helix B was connected by copper wires with a galvanometer three feet from the ring. The helices of A were connected end to end so as to form one common helix, the extremities of which were connected with a battery of ten pairs of plates four inches square. The galvanometer was immediately affected, and to a degree far beyond what has been described when with a battery of tenfold power helices *without iron* were used (10); but though the contact was continued, the effect was not permanent, for the needle soon came to rest in its natural position, as if quite indifferent to the attached electro-magnetic arrangement. Upon breaking the contact with the battery, the needle was again powerfully deflected, but in the contrary direction to that induced in the first instance."[10]

From this point on, the multitudinous phenomena of electromagnetic induction unfolded themselves to Faraday's nimble mind and fingers with amazing rapidity. It was at this period that he simplified thought for himself and for all of us by introducing the idea of lines of force to represent an electric or a magnetic field in direction and relative intensity. So clear was his vision that he succeeded within a few days in devising a direct current generator which he describes as follows in this same Royal Society paper.

> "85. A disc of copper, twelve inches in diameter, and about one fifth of an inch in thickness, fixed upon a brass axis, was mounted in frames so as to allow of revolution either vertically or horizontally, its edge being at the same time introduced more or less between the magnetic poles (fig. 7). The edge of the plate was well amalgamated

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[10] *Experimental Researches*, series I, paragraphs 27–28.

for the purpose of obtaining a good but moveable contact, and a part round the axis was also prepared in a similar manner.

"89. It was difficult under the circumstances to make the contact between the conductor and the edge of the revolving disc uniformly good and extensive; it was also difficult in the first experiments to obtain a regular velocity of rotation; both these causes tended to retain the needle in a continual state of vibration; but no difficulty existed in ascertaining to which side it was deflected, or generally, about what line it vibrated. Afterwards, when the experiments were made more carefully, a permanent deflection of the needle of nearly 45° could be sustained.

"90. Here therefore was demonstrated the production of a permanent current of electricity by ordinary magnets (57).

"91. When the motion of the disc was reversed, every other circumstance remaining the same, the galvanometer needle was deflected with equal power as before; but the deflection was on the opposite side, and the current of electricity evolved, therefore, the reverse of the former."[11]

This little copper disk cutting the lines of force which run from the north to the south pole of a magnet and thus furnishing a minute but direct current, remained a scientific curiosity for more than thirty years, its commercial value not being recognized until the late sixties. The large industrial concerns of those days did not have a representative at each session of the Royal Society. The leading scientific periodicals of this time are flooded with repetitions, variations, and extensions of Faraday's discovery. Ampère and A. C. Becquerel in France, Nobili and Antinori in Italy, A. de la Rive in Switzerland, Lenz in Russia, and Poggendorff in Germany all exhibit intense interest in what was doubtess the greatest scientific novelty of the day. It now became possible, for the first time, to explain the deflection of a compass needle observed by Arago, when he rotated a copper disk immediately below or above the needle. Faraday's views concerning the magnetic field—the electrotonic state as he called it—may be traced in the following paragraphs of his *Experimental Researches*, 60, 242, 1114, 1661, 1729, 1733, and 3269.

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[11] *Experimental Researches*, series I, paragraphs 85–91.

LENZ'S LAW

Of all the various view-points which were offered about this time, the simplest and clearest is perhaps that which Emil Lenz presented to the Academy of Sciences at St. Petersburg on November 29, 1833.[12] Lenz takes a great variety of typical cases of induced currents and shows that in each case the sense of the induced current is such that the ponderomotive forces on the conductor tend to oppose the motion which produces the current.

THE ORIGIN OF MODERN ELECTRICAL UNITS

The present day student of electromagnetism in looking over the literature of this subject which appeared in the early thirties, is amazed to find that nearly all the work reported is purely qualitative; at most, one finds only rough comparisons of the quantities involved; a small current is described as one which barely moves a galvanometer needle; a large current is one which makes it turn around through two or three complete revolutions.

A striking exception to this is the great paper by C. F.

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[12] Reprinted in *Poggendorff's Annalen*, 31, pp. 483–494, 1834.

Gauss, (1777–1855) "On the Intensity of the Earth's Magnetic Force Expressed in Absolute Measure" which he read before the Royal Society of Sciences at Göttingen in 1833.[13] Here for the first time, magnetic measurements are reduced to those of ordinary mechanics. Gauss' style is so clear, so simple, so consecutive and so compelling in its logic that the reader finds the absolute system of measurement completely developed almost before he knows it. The experimental results which conclude the paper place the method upon a firm and practicable foundation.

First of all, the inverse square law is invoked to define the unit magnet pole; then the earth's field is defined in the following words, "Die Intensität des Erdmagnetismus aber muss bestimmt werden durch die bewegende Kraft, welche sie auf die Einheit der freien magnetischen Flüssigkeit ausübt" *l. c.*, p. 257. Next came the difficult problem of realizing or avoiding in the laboratory the fiction of a unit magnet pole. This he does by the now well known method of combining the two poles of opposite sign into a quantity which is called magnetic moment, which if not easily measured, is at least perfectly definite in thought and reasonably constant for any magnet which is carefully handled. The final step in Gauss' procedure is to outline two very simple experiments—still used in all teaching laboratories—one of which yields the data necessary to give the *product* of the earth's field and the magnetic moment of the magnet used, the other furnishes data for the *ratio* of the same two quantities. The computation of the earth's magnetic field in terms of the three fundamental units requires only the elimination of the moment of the magnet between the two expressions just mentioned.

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[13] Printed in *Poggendorff's Annalen*, 28, pp. 241–273, 591–615, 1833.

The plan thus initiated by Gauss has since been extended to electrical quantities and to other magnetic quantities. It was largely through conventions adopted by Section A of the Birtish Association for the Advancement of Science, by several international electrical congresses, and by various governments, that a similar absolute system—the system of the centimeter, the gram, and the second—has been adopted by the entire civilized world.

Faraday's mode of representing a vector field by means of lines of force had now acquired a new significance; the dip and the declination had long been known and had given us the direction of the field; but these measurements of Gauss told us just how close together the lines of force must be drawn. It now became possible also to compare the intensity of the earth's field at any one time and place with that at any other time and place, with complete independence of any changes in the apparatus which may have taken place in the meantime.

THE FORMULATION OF THE TWO LAWS OF ELECTROMAGNETISM

A convenient formulation of a law appears sometimes to be almost as important as the invention of the law itself. So it proved in the case of the second law of electromagnetism, a quantitative description of which seems first to have been given by F. E. Neumann (1798–1895) in the year 1845. It is to Neumann that we owe a convenient expression for the E. M. F. which acts in any circuit at the instant when a current is being induced in that circuit.

Neumann began life as a soldier, leaving the University of Berlin at the age of seventeen to serve as a volunteer in the campaign against Napoleon; later he was appointed to a full professorship of mineralogy and physics at the university of Königsberg: but he was also an accomplished mathematician. The form in which he expresses the E. M. F. of the induced current is not, therefore, the simplest possible, as will be seen by anyone who reads his memoir presented to the Berlin Academy on October 27, 1845, and reprinted in Ostwald's *Klassiker*. The essence of the matter, however, is this: Given a closed metallic circuit, a current is induced in this circuit whenever the number of lines of magnetic force threading the circuit is changed: and the electromotive force acting in the circuit at any instant is numerically equal to the rate at which the number of lines of force is changing, where it is always to be remembered that the direction of the induced current is opposite to that of a current which of itself would produce the same lines of force.

Electrical engineers express all this very simply by saying that the induced E. M. F. is the negative differential coefficient of the magnetic induction with respect to the time, that is, $-\frac{dN}{dt}$: or, in other words, this E. M. F. is determined by the rate at which the circuit is losing or gaining lines of force. When one wishes to compute such an E. M. F. in the laboratory he finds it most convenient to go back to coefficients of self and mutual induction which involve the ideas of Neumann.

Kelvin and Maxwell have expressed the value of N in what is probably the clearest possible way by considering the lines of force which thread any given circuit as made up of three parts, namely, those lines due to any current in the circuit itself, those due to current in a neighboring circuit, and those produced by a neighboring magnet.

The number of lines threading a circuit due to unit current in that circuit is called its coefficient of self-induction, generally denoted by L; the number produced by unit current in a nearby circuit is called the coefficient of mutual induction of the system, generally denoted by M; and those produced by a magnet can be represented as the sum of the products of the induction and area taken over the entire area of the circuit $-\ \Sigma(\mathrm{Ba})$, say. The Englishman's coefficient of mutual induction is what Neumann called the "mutual potential" of the system; and his coefficient of self-induction is Neumann's "potential of the circuit on itself."

Accordingly one may think of Neumann's coefficients as represented for all practical purposes by L and M; so that N may be written,

$$N = Li_1 + Mi_2 + \Sigma\ (\mathrm{Ba})$$

where i_1 is the current in the given circuit and i_2 that in the neighboring circuit. The great merit of Neumann's work lies in the fact that he proved that L and M are purely geometrical quantities; and that therefore an E. M. F. may, in general, be induced in the given circuit by changing the value of either current

i_1 or i_2, by changing the shape or position of either circuit, or by changing the field H produced by the magnet, and that all of these cases are summarized in the one brief expression

$$\text{E.M.F.} = -\frac{dN}{dt}$$

every letter of which bristles with meaning for any serious student of physics. These coefficients, L and M, grouped under the general head of *inductance*, are difficult to compute, even for simple cases; but once having evaluated a standard, it is a matter of comparative ease to compare with it (measure) any other inductance.

Some years after Neumann's law of induction was announced, it was shown that as a consequence of Biot and Savart's law, the work done in carrying a unit magnet pole once around a wire conveying a current is 4π times the strength of that current; and that it here matters not at all what path is taken by the unit pole in its round trip. Let us denote the current strength by i and the work done on unit pole by W; then the two laws of electromagnetism, the discoveries of Oersted and Faraday, respectively, may be expressed in the following crystalline and immensely valuable form:

$$W = 4\pi \mathrm{i}$$

$$\text{E.M.F.} = -\frac{dN}{dt}$$

AN EXTENSION OF THE IDEA OF THE ELECTRIC CIRCUIT

In his *Defence of Poesie*, Sir Philip Sidney, a lad of ten summers in the year Galileo was born, reckons among the marks of a liberal education a certain "enlargement of conceit." A widened vision of this kind was precisely what students of electricity acquired in the early fifties when W. Weber (1804–1891) first showed how to measure electrical resistances in absolute measure, and when Lord Kelvin generalized the theory of the voltaic circuit so as to include the open (or unclosed) circuit.

Weber's great paper[14] gave to Ohm's law for the first time perfect definiteness and precision. The discussion is marked by that clarity and simplicity which is characteristic of a master mind whatever the language in which he writes. The procedure is as follows: Start with Gauss' determination of the earth's magnetic field, H, in absolute units; then Neumann's expression for the E. M. F. induced in a single turn of wire bent into a circle and rotated through 90 degrees in the earth's field becomes, E. M. F. $= \frac{\pi R^2 H}{t}$, where R is the radius of the circuit and t the time required to turn it out of the magnetic meridian into a plane at right angles to the meridian. This, he points out, is equivalent to taking for unit E. M. F. that which obtains in a wire which cuts one line of magnetic force per second.

The next problem is to measure the current in absolute measure; and this Weber accomplishes by using the magnetic shell of Ampère; in other words, he adopts as unit of current that current which flowing about a circuit of unit area will have the same effect on a compass needle as will a magnet of unit moment. Or if i be the strength of current flowing in a circular circuit of radius R, then it is equivalent to a magnet of moment M where

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[14] *Poggendorff's Annalen*, 82, 337–369, 1851.

$$M = \pi R^2 i \quad \text{or} \quad i = M/\pi R^2$$

M is here to be considered as an easily measured quantity since the magnetic field, H', which a coil of wire produces at a given distance, r, is simply measured and the equivalent magnet has its moment determined by the fact that

$$H' = \frac{M}{r^3}, \text{ or, } M = H' r^3; \text{ whence } i = \frac{H' r^3}{\pi R^2}$$

Thus, having reduced both E. M. F. and current to absolute measure, Weber computed at once the absolute resistance of his circuit from Ohm's law

$$\text{Resistance} = \frac{E.M.F.}{i} = \pi^2 \left(\frac{R}{r}\right)^3 \left(\frac{H}{H'}\right) \left(\frac{R}{t}\right)$$

where each quantity in the right hand member is purely mechanical, except the two magnetic fields; and these enter only as a ratio, which is a pure number. These experiments accordingly gave the value of the resistance of the circuit in absolute units, centimeters and seconds. In practice, Weber found that it was more practicable to measure the total quantity of electricity induced than the current strength. This total quantity is merely the time integral of the current for which a galvanometer needle acts as an integrating device, the relation between the throw of the needle and the quantity of electricity passed being well known.

All this, however, is merely an experimental detail, the important fact is that Weber first showed us how to reduce this fundamental electrical quantity, resistance, to ordinary mechanical units. Vastly better methods were afterwards devised by Kirchhoff, Lorenz, Rosa, and others; but these lie beyond the bounds of this sketch.

As a corollary to the measurements which Weber made upon certain copper wires, he proceeded to define *specific resistance* in absolute measure, as the resistance of a wire of unit length and unit cross-section; his definition departs from modern usage only in employing millimeters and seconds instead of centimeters and seconds.

In this same year, 1851, Lord Kelvin pushed the dynamics of the electric circuit a step farther by proving that, in general, the rate at which an electric current does work in any part of the circuit is measured by the product of the current and the E. M. F. in that part of the circuit. This extension of the law which Joule and Helmholtz had already proved for the case in which the work of the current is spent in heat is found in the *Philosophical Magazine* for December, 1851.

Two years later, Kelvin established a general theorem that the energy of any field of force, electric or magnetic, is the volume integral of the product of induction by intensity taken throughout the field and divided by 8π. It is thus evident that the science of electromagnetism was year by year being brought over into close contact with the domain of dynamics. A few years later (1860) Kelvin transforms the electromagnetic energy in the field of a closed circuit into the simple expression $1/2\ L\ i^2$, where the quantity L, called by him the "electrodynamic capacity" of the circuit, is, of course, identical with the modern coefficient of self-induction. The energy of the field is thus brought into the same form with that of kinetic energy in general and with the electrostatic energy of a charged condenser, $\frac{1}{2}$ C V^2.

An earlier and very distinct achievement in this union of electricity and dynamics was the derivation of Neumann's expression for the E. M. F. of induced currents by Helmholtz (1821–1894) in his brilliant essay *On the Conservation of Energy* (Berlin, 1847). Here, almost with a stroke of the pen, Helmholtz equates the energy supplied by the voltaic cell during any small interval of time to the Joule heat plus the change in the kinetic energy of a magnet attracted by the battery circuit. The invariant sum contemplated by the energy principle is here made up of three items, namely, the chemical energy of the cell, the heat energy of the wire, and the kinetic energy of the moving magnet.

The equation thus obtained for the induced current assumes at once a form which is equivalent to that usually given to Ohm's law, except that in the numerator there appears, in addition to the E. M. F. of the voltaic cell, also a term, $-\frac{dN}{dt}$, which is nothing else than Neumann's expression for the E. M. F. of the induced current.

THE OPEN CIRCUIT

Heretofore all the great electricians, including Ampère, Neumann, and Weber, had confined their efforts mainly to closed circuits. Kelvin, however, in 1853, undertook the problem of describing what happens in an unclosed or open circuit, made up of a resistance, *R*, an inductance, *L*, and a capacity, *C*, in series. He supposes the condenser to be given a charge, *Q*, by any external means which may be convenient, and then left to itself. It had been long suspected that, under certain conditions, the discharge of such a condenser is oscillatory in nature. The suggestion had, indeed, been made by Savary in 1827, by Joseph Henry in 1842 and again by Helmholtz in 1847. Kelvin built up his descriptive equation by putting the loss of potential energy in the condenser, *C*, equal to the Joule heat generated in the resistance, *R*, plus the electromagnetic energy stored up in the space about the inductance, *L;* but this immediately transforms into an expression which makes the potential difference of the condenser plates, *C*, at any instant equal to the induced E. M. F. in the coil *L* plus the drop of potential in the resistance *R*. The equation thus obtained he recognized at once as being that of a loaded spring vibrating freely in a viscous medium; and proceeded farther

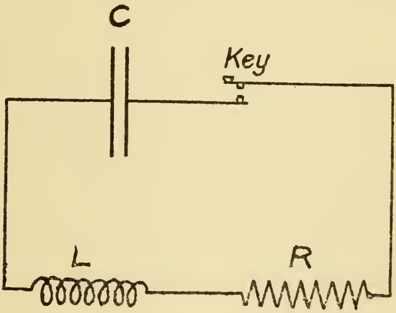

FIG. 12. THE OPEN ELECTRIC CIRCUIT

to point out precisely what the circumstances are which determine whether the discharge shall be oscillatory or "dead beat." From this time on there was no doubt that the rôle of inductance, L, in the electric circuit is identical with that of the load in the spring; the resistance R acts as the viscosity of the medium upon the spring; while the elasticity of the spring is represented, not by the capacity of the condenser, but by its reciprocal. As a boon to clear thinking it is difficult to overestimate the value of this analogy for later generations.[15]

The ideas involved in the solution of the problem of the open circuit were shortly afterwards put to splendid use by Kelvin, Stokes and others in the solution of the new and tremendously difficult problem of signalling through an Atlantic cable. The manner in which Kelvin built up the electrical equivalent of a submarine cable in his laboratory at Glasgow, and the manner in which the first Atlantic cable was ruined by disregarding his operating instructions is a story well known to all electric engineers.

We are now within a single decade of the time when Maxwell succeeded in completely abolishing the idea of "open circuits" from the domain of physics. There is, however, one more preliminary step—that of the medium —which we must take up before reaching Maxwell's work.

THE MEDIUM WHICH TRANSMITS ELECTROMAGNETIC FORCES

It was a matter of considerable surprise to men of science in 1879 when they then learned—most of them for the first time—that what is essentially the same physical quantity which we now call "electric potential" was employed by Henry Cavendish as early as the year 1771 under the name of "degree of electrification." This was made very clear by Maxwell in his edition of *The Electrical Researches of Henry Cavendish* which was published by the Cambridge University Press in 1879, only a few weeks before the death of its editor. This volume is really a new contribution to knowledge; for Maxwell repeated and verified many of Cavendish's experiments essentially in their original form.

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[15] Kelvin's paper is to be found in *Philosophical Magazine*, 5, 1853; also in his *Mathematical and Physical Papers*, I, p. 540.

Cavendish (1731–1810) was a recluse in spite of the fact that he was one of the wealthiest men in England; but he preferred rather to pursue the truth than to publish it and was exceedingly negligent of his own scientific reputation. All his electrical work is distinguished by its cleverness and by its extraordinary accuracy. His two great achievements, outside the domain of electricity, are his discovery of the compound nature of water (1785) and his determination of the density of the earth (1798).

In the field of electricity, he is not only to be considered as having established the fundamental equation of electrostatics; namely, the relation between quantity and potential, $Q = CV$, but also as the first to measure carefully the constant C which we now call "capacity." He went even farther and showed how the capacity of a pair of plates is increased by replacing the air between them by some other medium, such as wax. All this was done without the use of a gold leaf electroscope which Bennett did not invent till 1787. His potentials—"degrees of electrification"—were measured by determining the length of gap through which a Lane unit jar would discharge. This electrometer of Lane's was a very clever and important quantitative instrument first described in a letter from Timothy Lane (1734–1807) to Benjamin Franklin dated October 15, 1766 and again described in the *Philosophical Transactions* for 1768.

Maxwell puts Cavendish's study of the dielectric with his customary clarity in the three following paragraphs.

> "The leading idea which distinguishes the electrical researches of Cavendish from those of his predecessors and contemporaries, is the introduction of the phrase 'degree of electrification' with a clear scientific definition, which shows that it is precisely equivalent to what we now call potential."

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> "He ascertained by a well-arranged series of experiments the ratios of the charges of a great number of bodies to that of a sphere 12.1 inches in diameter, and as he had already proved that the charges of similar bodies are in the ratio of their linear dimensions, he expressed the charge of any given body in terms of the diameter of the sphere, which, when equally electrified, would have an equal charge, so that when in his private journals he speaks of the charge of a body as being so many 'globular inches,' or more briefly, so many 'inches of electricity,' he means that the capacity of the body is equal to that of a sphere whose diameter is that number of inches."

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> "But the observed charges of coated plates were found to be always several times greater than the charges computed from their thickness and the area of their coatings, the ratio of the observed charge to the computed charge being for plate glass about 8.2, for crown glass about 8.5, for shellac about 4.47, and for bees' wax about 3.5. Thus Cavendish not only anticipated Faraday's discovery of the Specific Inductive Capacity of different substances, but measured its numerical value in several substances."[16]

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[16] *Scientific Papers of the Hon. Henry Cavendish*, I, pp. 18–21, Cambridge University Press, 1921.

So few of Cavendish's results were published at the time when they were obtained that it was left to Faraday, more than half a century later, to rediscover many of his methods and ideas. In series XI of his *Experimental Researches*, 1837, Faraday takes up the general question as to whether different materials exert any influence over the amount of induction that takes place through them. His answer is experimental, affirmative, and quantitative. For example, by comparing the capacities of two similar condensers of the same dimensions, one having air, the other sulphur, as a dielectric, he establishes the fact that the effect of the sulphur is to increase the capacity of its condenser 2.24 times. §1275. From such data, he infers that

> "Induction is essentially an action of contiguous particles, through the intermediation of which the electric force, originating or appearing at a certain place, is propogated to or sustained at a distance." §1295. "The direct inductive force, which may be conceived to be exerted in lines between the two limiting and charged conducting surfaces, is accompanied by a lateral or transverse force equivalent to a dilatation or repulsion of these representative lines." §1297.

To this property which the dielectric possesses of increasing the capacity of a condenser Faraday gave the name *specific inductive capacity*, a synonym of the modern *dielectric constant*. The experimental facts just mentioned added immensely to Faraday's confidence in the view that the attraction or repulsion of one electrified body upon another is not a case of action at a distance but a case in which the force is handed on from point to point through the medium. With these results of Faraday and his picture of the electric and magnetic fields in terms of lines of force, Maxwell enters upon the scene with his epoch-making paper, read before the Royal Society of London on December 8, 1864.

THE FARADAY-MAXWELL ELECTROMAGNETIC THEORY

Maxwell's view of the electromagnetic field is based upon a small group of fundamental experimental facts. From these he derives a symmetrical, simple and orderly description of the whole domain of electromagnetism which is one of the most beautiful creations in the entire history of electricity. A rough sketch of this structure would be something like the following. Maxwell starts with three distinct properties of matter; namely, electric conductivity, dielectric constant, and magnetic permeability. The developmental history of these three quantities we have already traced. The well-known phenomena connecting these quantities with the electrical and magnetic fields and with mechanical forces are described in twenty independent equations involving twenty variable quantities.

The essential feature of this discussion which forms Part III of Maxwell's Royal Society paper of 1864 is the following set of seven equations, in which K denotes the dielectric constant, ρ the resistivity, and μ the permeability of the medium; E and H indicate the strengths of the electric and magnetic fields respectively; D the displacement, u the density of the conduction current and B the magnetic induction at the point under consideration.

$$D = \frac{K\,E}{4\,\pi}, \quad \text{The Equation of Electric Elasticity.}$$

$u = \frac{E}{\rho}$, The Equation of Electric Resistivity.

$B = \mu H$, The Equation of Magnetic Permeability.

Assuming now that the medium is isotropic and uncharged, and that the total current density i is the sum of the conduction current and the displacement current $\frac{K}{4\pi} \frac{\partial E}{\partial t}$, the other four equations take the following form in vector notation.

$\text{div. } i = 0,$ Divergence of current.

$\text{div. } B = 0,$ Divergence of magnetic induction.

$- \text{Curl } E = \frac{\mu}{c} \frac{\partial H}{\partial t}$ The equation of magnetic force.

$\text{Curl } H = \frac{1}{c} \cdot 4\pi i$ The equation of current.

Here c is the ratio of the electromagnetic to the electrostatic unit of quantity. These last four equations—generally known as Maxwell's equations—form the most general description of the magnetic field in a medium which is uncharged and which is isotropic. On the same ground that $\frac{\partial D}{\partial t}$ is called the electric displacement current, $\frac{\partial H}{\partial t}$ might, as Professor A. G. Webster suggested, be called the magnetic displacement current.

To make these equations applicable to electromagnetic disturbances which occur in free space such, for example, as those which one meets in wireless telephony or in ordinary light waves *in vacuo*, it is necessary only to put $\mu = K = 1$.

THE ELECTROMAGNETIC THEORY OF LIGHT

As Maxwell pointed out, in his *Treatise*, §799, "most transparent solid bodies are good insulators and all good conductors are very opaque." It seems therefore strictly in accordance with fact to put the conductivity, $1/\rho$, equal to zero for media in which one is considering the propagation of light. When this is done Maxwell's equations assume the following symmetrical form.

$$-\text{Curl } E = \frac{\mu}{c}\frac{\partial H}{\partial t}$$

$$\text{Curl } H = \frac{K}{c}\frac{\partial E}{\partial t}$$

Between these two equations for the curls of the fields, H and E, it is possible to eliminate either H or E, and thus obtain a differential equation describing the other field as a function of t; and this is precisely what Maxwell did. Whichever of the two fields is eliminated the result is a differential equation involving only one dependent variable and having a well-known form which was solved by d'Alembert, the great encyclopaedist, a full century before the time of Maxwell. For reasons which will appear immediately, this expression is known as the *equation of wave propagation.* The differential equation and its integral are as follows:

$$\frac{\partial^2 E}{\partial t^2} = \frac{c^2}{K\mu}\frac{\partial^2 E}{\partial x^2}$$

$$E = f_1\left(x - \frac{c}{\sqrt{K\mu}}t\right) + f_2\left(x + \frac{c}{\sqrt{K\mu}}t\right)$$

where f_1 and f_2 denote arbitrary functions.

By eliminating E, one obtains a similar pair of equations for H. The speed of the waves is measured by the coefficient of t and hence, Maxwell pointed out, the speed of such waves in free space, where $\mu = K = 1$, is numerically equal to the ratio of the ordinary electromagnetic and electrostatic units.

Maxwell's next step was to propose that, since the computed speed of these hypothetical electric waves is almost identical with the observed velocity of light, it is highly probable that light waves are also electromagnetic waves.

The above is a brief outline of what Maxwell accomplished in his great paper of 1864 on the electromagnetic field; the notation is along the lines of that used by Oliver Heaviside (1850–1925). The coefficients k, μ, ρ, here employed, are merely experimentally determined constants; they give no picture of the chemical constitution or structure of matter; they are properties not of particular bodies but of substances.

One striking defect of the theory was recognized by Maxwell himself; his results apply only to very long wavelengths, since only in this case are the electrical processes comparable with those employed in measuring the permeability and dielectric constant of the medium. Maxwell's theory indeed gives the same value of the refractive index for light of all colors. The explanation of this discrepancy between theory and fact was largely removed when in 1898 the electron was discovered and dispersion was explained in terms of the periodic motion of charged electrons associated with the molecules of the medium. This leads to a large field quite beyond the range of this sketch.

Maxwell had made clear in his electromagnetic theory that the permeability of the medium plays the same rôle as density in the case of ordinary elastic waves. It was also clear that the reciprocal of the dielectric constant took the part of stiffness or rigidity in common elastic media. The equations of Maxwell describe the manner in which any electromagnetic disturbance is propagated; but as yet, however, no one had succeeded in producing anything but electromagnetic pulses. Joseph Henry commented upon disturbances of this kind which he obtained when he interrupted the "energizing" current of his big magnet. It is practically impossible, however, to study in an experimental way the speed of a single pulse of this type. It is remarkable that G. Kirchhoff had adumbrated the modern view in his great paper on "The Motion of Electricity in Wires"[17] in which he shows, on the basis of the older theory, that the equation describing an electric wave on a wire is analogous to that of a wave in a stretched string and travels with a speed "sehr nahe gleich der Geschwindigkeit des Lichtes in leeren Raume."

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[17] *Poggendorff's Annalen*, **100**, 193, 1857.

Maxwell's electromagnetic theory was at the time of its promulgation rather devoid of experimental verification. Furthermore, it involved the vital assumption that an electric charge displaced, say, from one end to the other of a molecule of a dielectric, will produce a magnetic effect identical with that of an ordinary conduction current. In other words, the theory assumed the following expression

Total current = *Conduction current* + *Displacement current.*

In 1873, appeared Maxwell's monumental treatise on *Electricity and Magnetism*, a highly original contribution marked especially by two brilliant chapters, one on the "Dynamical Theory of Electromagnetism" and the other on the "Electromagnetic Theory of Light." The latter theory, however, did not receive ready acceptance. To reduce optics to a mere branch of electromagnetism was still regarded as somewhat fanciful, not to say bizarre.

Three years later, that is in 1876, H. A. Rowland proved by his justly celebrated "Berlin experiment" that an ordinary electrostatic charge, carried on a rapidly rotating ebonite disk, produces a magnetic field identical in amount and direction with that produced by a conduction current of proper size in a geometrically similar circuit.

In spite of this cogent evidence, however, not many accepted the Maxwellian theory of light. Helmholtz and Rowland were practically alone in using it in their university lectures. Oliver Heaviside advocated it. A few men wrote books about it. Lord Kelvin insisted that he did not understand it. In the first of his *Baltimore Lectures* given before Johns Hopkins University in the autumn of 1884, this leading physicist of English-speaking people pays his respects to the electromagnetic theory of light in the following words.

> "If I knew what the electro-magnetic theory of light is, I might be able to think of it in relation to the fundamental principles of the wave theory of light. But it seems to me that it is rather a backward step from an absolutely definite mechanical notion that is put before us by Fresnel and his followers to take up the so-called Electromagnetic theory of light in the way it has been taken up by several writers of late. In passing, I may say that the one thing about it that seems intelligible to me, I do not think is admissible. What I mean is, that there should be an electric displacement perpendicular to the line of propagation and a magnetic disturbance perpendicular to both. It seems to me that when we have an electro-magnetic theory of light, we shall see electric displacement as in the direction of propagation, and simple vibrations as described by Fresnel with lines of vibration perpendicular to the line of propagation, for the motion actually constituting light. I merely say this in passing, as perhaps some apology is necessary for my insisting upon the plain matter-of-fact dynamics and the true elastic solid as giving what seems to me the only tenable foundation for the wave theory of light in the present state of our knowledge."[18]

Nor was Lord Kelvin alone in these views; for, as Professor Pupin remarks in his presidential address before the American Association for the Advancement of Science referring to this same period,

> "There were, in those days, very few scientists in England or anywhere else who understood clearly Maxwell's meaning. Heaviside was certainly one of these chosen few, but his extraordinary mathematical exuberance obscured to the non-mathematical mind of the telephone engineer his interpretation of Maxwell."

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[18] Kelvin, *Baltimore Lectures*, p. 9.

HERTZ'S EXPERIMENTS

Five years before these lectures of Kelvin, Helmholtz had set the following question for one of the great prizes of the Berlin Academy, "whether the polarization and depolarization of an insulator should produce in its neighborhood the same electromagnetic effects as a galvanic current in a conductor."[19]

The remarkable experiments by which Heinrich R. Hertz (1857–1894) obtained an answer to this question in the autumn of 1887 and thus inaugurated a new era in the history of physics is already so widely known as to call for only brief comment. Among the brilliant group of men who had studied under Helmholtz, Hertz was the favorite student. He had obtained his doctorate in 1880, *summa cum laude*, and was professor of physics in the Polytechnic School at Karlsruhe during the years between 1885 and 1889.

In the year 1887, he succeeded not only in setting up an oscillatory circuit as Feddersen had done a quarter century earlier, but he produced electrical vibrations a hundred times more rapid than those of Feddersen.

The transversal waves thus set up had wavelengths sufficiently small to be observed inside the lecture room of the laboratory at Karlsruhe. On being reflected from a wall covered with sheet zinc these reflected waves interfered with the incident waves and produced a set of stationary waves, the length of which were measured by use of a "secondary conductor"—a resonant circle of copper wire, containing a minute spark gap.

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[19] Helmholtz's Preface to *Hertz's Principles of Mechanics*, Jones' translation, p. xiv.

The wavelengths thus measured were used to compute the period of the vibration by assuming the speed of these waves to be identical with that of light. On this basis Hertz obtained a period of 1.55 hundred-millionths of a second, instead of 1.4 hundred-millionths obtained from the capacity and self induction of the oscillatory circuit. Concerning the interpretation of this work, Hertz has the following to say.

> "I have described the present set of experiments, as also the first set on the propagation of induction, without paying special regard to any particular theory; and, indeed, the demonstrative power of the experiments is independent of any particular theory. Nevertheless, it is clear that the experiments amount to so many reasons in favour of that theory of electromagnetic phenomena which was first developed by Maxwell from Faraday's views. It also appears to me that the hypothesis as to the nature of light which is connected with that theory now forces itself upon the mind with still stronger reason than heretofore. Certainly it is a fascinating idea that the processes in air which we have been investigating represent to us on a millionfold larger scale the same processes which go on in the neighbourhood of a Fresnel mirror or between the glass plates used for exhibiting Newton's rings."[20]

The clearest, the simplest, and the most illuminating account of these Karlsruhe experiments ever given is doubtless that which is to be found in the public lecture which Hertz gave before the German Association for the Advancement of Natural Science and Medicine, in Heidelberg on September 20, 1889.[21] Here the whole matter is set forth in words of one syllable, so to speak. A fascinating picture of Hertz's preliminary report on this work to the Berlin Academy has been drawn by Professor Pupin who was present at the meeting in 1887.[22]

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[20] *Wiedemann's Annalen*, 34, p. 622, 1888.

[21] Hertz, *Miscellaneous Papers*, translated by Jones, pp. 313–327.

The experiments of Hertz were, of course, repeated all over the world just as those of Volta, Oersted, Seebeck, and Faraday had been in the early part of the century. The resonating circle of Hertz was soon displaced by detectors of immensely greater sensibility, such as the vacuum tube of Lecher, the coherer of Branly, the magnetic detector of Rutherford. One of the most energetic and effective of the workers who established the analogy between electric waves and light waves was the late Professor A. Righi (1850–1920) of Bologna.

One day a young man by the name of Marconi called at Righi's laboratory and asked how one could increase the distance at which electric waves are detectable. Righi's reply was "Make your oscillators longer." Following this clue, Marconi was able to bridge the English channel in 1899; and in 1901, he succeeded in sending signals from England to Newfoundland, where a succession of "S's" were detected by means of a coherer.[23]

THE ERA OF THE VACUUM TUBE

The next great step in electromagnetism is one which was made possible by a discovery of Thomas A. Edison. This new phenomenon which Edison exhibited at the Electrical Exposition in Philadelphia in 1884 and which

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[22] The sketch appears in his *From Immigrant to Inventor*, pp. 263–272, Scribner, 1924.

[23] G. Marconi, *Proceedings of the Royal Institution*, 17, 195–210, 1902.

W. H. Preece more thoroughly investigated[24] consists in the fact that when a metallic plate is sealed into an ordinary incandescent electric light bulb, alongside the ordinary filament, one can obtain a considerable current—say a milliampere or so—by joining the metallic plate to the positive end of the heated filament, but will obtain almost no current by joining the plate to the negative terminal of the filament. This "Edison effect" is, of course, not an electromagnetic discovery; but it was so brilliantly used a quarter century later (1907) by Dr. Lee De Forest in wireless telegraphy that its history finds its proper place in this chapter. The modern *kenetron* employs the Edison effect for rectifying high tension currents such as are employed in X-ray work. A two electrode vacuum tube of this kind allowing current to pass only in one direction—here from the plate to the filament—has come to be known as an *electric valve*. At the very close of the century, Sir J. J. Thomson showed that the current which Edison first observed is in fact a procession of negatively charged electrons from the filament to the plate.

What De Forest did was to seal into the bulb a third electrode in the shape of a small grid of platinum wires. Then it was observed that when the plate was given a positive potential by means of a battery the procession of electrons from filament to plate becomes tremendously sensitive to a rise or fall of potential of this grid. The three-electrode vacuum tube thus showed itself vastly more sensitive than any other form of detector; for when one connects the receiving antenna (either directly or through a transformer) to the grid, the very slight changes of potential at the grid make large changes in the plate current. A negative potential given to the grid hinders the torrent of electrons passing to the plate; while a positive potential aids it. The variations thus produced in the plate current are in general easily detected by a telephone placed in circuit; but if changes in the procession of electrons are too slight for this, they can be applied to the grid of a second three-electrode tube—or *triode* as it is now frequently called—which thus acts as an amplifier.

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[24] *Proceedings of the Royal Society*, 38, p. 219, London, 1885.

A third function of the triode was soon discovered by E. H. Armstrong who in 1914 patented his regenerative circuit—commonly known as "the feed back"—and showed that by passing the plate current through an oscillation transformer and by connecting its secondary circuit to the filament and the grid, we have an oscillatory circuit capable of producing sustained oscillations on the same principle as that of the "howling telephone." Here then we have a device which displaced the "singing arc" and served as the starting point of modern wireless telephony. The independent discovery of this regenerative principle is also claimed for Alexander Meissner of Berlin.

The three great steps in radio communication are then the creation of the theory of the electromagnetic waves by Maxwell in 1864, the experimental realization of these waves in the laboratory by Hertz in 1888, and the invention of the three-electrode tube with its grid by De Forest in 1907. The present state of the science of electromagnetism is the product of approximately a century of work; that of radio-communication a half century.

The human voice was heard across the Atlantic for the first time in 1915, when words spoken by the engineers of the Bell Telephone System at Arlington, Virginia, were audible at the Eiffel tower in Paris. A few years later (January, 1923) a large group of persons in London were able to hear with ease a message spoken in the offices of the American Telephone and Telegraph Company in New York. The British Post Office opened its high power station at Rugby on January 1, 1926, for the transmission of messages to vessels in any part of the world. All this has been made possible by high power water-cooled vacuum tubes and various other improvements. Regular telephone service between England and the United States was first opened in the early part of 1927.

Limitations of space and time do not permit us to follow a host of important applications, such as the invention of the dynamo about the year 1867 by Wilde, Varley, Siemens and Wheatstone, the dynamo being merely a generator with a self-excited electromagnet for producing the field.

If the first chapter in the history of electrical engineering, as distinguished from electrical science, may fairly be said to begin with Kelvin's solution of the problems connected with the laying of the Atlantic cable, then the *second* chapter begins with the invention of the slotted iron ring armature by Pacinotti in 1864. The idea of such a toothed iron armature occurred to Pacinotti while he was serving as a soldier in the campaign of Garibaldi in 1859; but it was not until 1865 when Pacinotti was Professor of Physics at the University of Pisa that he perfected the invention and described it in *Il nuovo cimento.* Gramme's invention of this armature in 1870 seems to

Antonio Pacinotti (1841–1912)
Italian physicist; inventor of the slotted iron ring armature

have been made quite independently of Pacinotti. The story of this invention is told in a charming little volume published by the Associazione Elettrotechnica Italiana. Here the original paper is reprinted and translated into four other languages.[25] The narrow limits of this sketch do not permit us farther to follow the marvelous development of the modern electromagnetic generator; or the telephone brought out by Graham Bell and Elisha Gray in 1876, or the modern transformer and other such devices which have powerfully affected our present civilization and which well deserve more consideration than can here be given.

One of the most brilliant applications of electromagnetic theory is that made by Professor M. I. Pupin in 1900 toward the elimination of distortion and attenuation from telephone circuits through cables. The difficulty of talking through cable circuits had been that the voice waves of different frequencies travelled through the cable with different speeds. Pupin, basing his argument upon electromagnetic theory and upon the analogy of the loaded violin string, showed how to construct a cable with distributed inductance which would offer practically the same impedance to all frequencies, and thus transmit the voice with a minimum of distortion. These "pupinized cables," as the French call them, are very widely used, both for telephony and telegraphy.

Here also belongs the story of those recent powerful electromagnets of Du Bois designed upon the principle of Ohm's law, as extended to the magnetic circuit by H. A. Rowland and Bosanquet. The latest, if not the last word in the production of electromagnets is to be found in Professor Weiss' pattern in which the wires conveying the current about the legs of the magnet are hollow and carry inside of them a stream of cool water, thus maintaining not only a large and powerful, but also a constant, magnetic field; for the variation of its strength which usually occurs when the iron core changes temperature, is here avoided.

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[25] *Descrizione di una Macchinetta Elettro-magnetica*, del Dr. Antonio Pacinotti, Bergamo, 1912.

The limits of this sketch now compel us to return to the story of light from which we broke off at the point where Young and Fresnel had firmly (?) established the fact that light consists of transverse waves in the ether.

CHAPTER XII

THE RISE OF MODERN SPECTROSCOPY

> "Time glides with undiscover'd haste
> The future but a length behind the past."
> —DRYDEN.

In an earlier chapter the work of Newton, Huygens, Young, and Fresnel in establishing the wave theory of light has been briefly considered. Attention was also directed to the observations of certain spectra by Fraunhofer and Wollaston. We pass now to the history of the methods which are employed for the production, analysis, and interpretation of these light rays: a branch of learning known as spectroscopy.

The history of this science clearly begins with Newton when, in 1672, he announced his discovery of the fact that white light is a mixture of various colors which are differently refracted by a glass prism; blue, the most; red, the least. To the colored band of light thus spread out Newton gave the name *spectrum*. For nearly a century following the publication of his *Opticks* in 1704, almost nothing was added to our knowledge of the spectrum.

The one striking exception to this statement is a contribution made to the Medical Society of Edinburgh by a young Scotsman, Thomas Melvill (1726–1753), just the year before his death. He describes what he saw when looking through a prism at an alcohol flame fed with alum, potash, and other substances. A pasteboard screen with a circular hole in it was placed between the eye and the flame. Under these conditions Melvill says,

> "All sorts of rays were emitted, but not in equal quantities; the yellow being vastly more copious than all the rest put together, and red more faint than the green and blue.
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> * * * * *
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> "Because the hole appears through the prism quite circular and uniform in color, the bright yellow which prevails so much over the other colors must be of one determined degree of refrangibility; and the transition from it to the fainter color adjoining, not gradual, but immediate."[1]

Here, more than a hundred years before the time of Kirchhoff and Bunsen, we have a distinct step forward in the field of spectrum analysis; for these are nothing less than the first reported observations on emission spectra.

In the last year of the eighteenth century, however, Sir William Herschel (1738–1822) extended the spectrum beyond the visible region by placing a sensitive thermometer just outside the red end and observing that, for some distance, the thermometer indicated not only a higher temperature than the room but also a higher temperature than the red of the spectrum band. That this effect is produced by *bona fide* heat rays, Herschel proved by showing that the radiation is reflected and refracted by mirrors and lenses just as the visible rays are.

Only a year later, J. W. Ritter (1776–1810) then of Jena, lengthened the spectrum at the other end by demonstrating that, away beyond the visible blue, the spectrum band had the power of blackening silver chloride.[2]

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[1] *Journal of the Royal Astronomical Society of Canada*, July and August, 1914. Both papers are reprinted in full.

[2] *Gilbert's Annalen*, 7, p. 527, 1801.

In the year following, it was observed for the first time that the spectrum of sunlight is crossed by dark lines. This discovery[3] was made by Dr. W. H. Wollaston (1766–1828), a London physician and a chemist well known for his discovery of the elements, palladium and rhodium. Wollaston says,

> "If a beam of daylight be admitted into a dark room by a crevice 1/20 of an inch broad, and received by the eye at a distance of 10 or 12 feet, through a prism of flint glass, *free from veins*, held near to the eye, the beam is seen to be separated into the following four colours only, red, yellowish green, blue and violet."

Such a method of viewing these dark lines is still a most excellent one for the beginning student; though a very narrow strip of white paper placed in bright sunlight is generally a more convenient source than a crevice in a dark room.

Wollaston was also the first to observe the spectrum of the blue light at the base of a candle flame—what is now called the Swan spectrum. Wollaston's paper[4] leaves little doubt that he considered the dark solar lines to be natural boundaries or discontinuities separating the different colors.

FROM FRAUNHOFER TO KIRCHHOFF AND BUNSEN

How far from the truth this view of Wollaston's is was made clear twelve years later when this same study was taken up by the German optician, Joseph Fraunhofer

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[3] *Philosophical Transactions*, II, pp. 365–380, 1802.

[4] Easily consulted in Ames' *Prismatic and Diffraction Spectra*, Harper's Scientific Memoirs.

(1787–1826) who examined the solar spectrum produced by a prism placed 24 feet away from a narrow slit illuminated by sunlight. The band of the spectrum was observed through the telescope of a theodolite placed immediately behind the prism. By this means Fraunhofer counted more than 700 dark lines and mapped over 300 of them within the limits of the visible spectrum. This work was done in 1814 and published by the Bavarian Academy in 1817. "The strongest lines," says Fraunhofer in contrast with Wollaston, "do not in any way mark the limits of the various colors; there is almost always the same color on both sides of a line, and the passage from one color into another cannot be noted."

To an optician interested in the manufacture of achromatic objectives, and therefore needing accurate values of refractive indices, this was a discovery of vast importance; and the letters which Fraunhofer attached to the stronger lines still serve, after more than a century, to indicate perfectly definite colors, refractive indices, and wavelengths. Fraunhofer was a natural born investigator and therefore went on to examine the spectra of *Mars* and *Venus* and certain of the fixed stars, among them *Sirius*, *Capella*, *Betelgeuse*, *Procyon*.

It was about this time (1819) that Biot and Fresnel were making clear the phenomena of diffraction; and upon this basis Fraunhofer proceeded to manufacture a great variety of plane gratings, wire wound on screws, diamond rulings on glass, on gold, etc. He thus measured the wavelengths of the principal dark lines of the solar spectrum with an accuracy of one part in a thousand. Spectra produced by diffraction through a single slit he called "spectra of the first class;" those produced by an ordinary grating of parallel threads or rulings he called "spectra of the second class;" while the secondary maxima which make their appearance when monochromatic light is viewed through a grating of few rulings—few open spaces—are grouped under the name of "spectra of the third class"—a distinction which has been a great aid to clear thought. This series of achievements must be considered as nothing less than laying the broad and firm foundation of the science of astrophysics.

As the reader will naturally expect, the next important step in spectroscopy is the correct interpretation of the physical significance of these Fraunhofer lines—a step which was made a third of a century later by Kirchhoff and Bunsen at Heidelberg. It would, however, be a grave error to imagine that the intervening period was one barren of important results. Some of these must be briefly indicated at least before we consider the launching of the new science of spectrum analysis at Heidelberg. The following eight steps are especially worthy of notice.

(i) The observation of absorption spectra in gases by Sir David Brewster, W. H. Miller and others.[5] To Brewster also are we indebted for the discovery that absorption lines make their appearance in the solar spectrum and exhibit a strong variation not only between summer and winter, but also with the elevation of the sun above the horizon. To these Brewster gave the name "atmospheric lines."[6] We now call them "terrestrial lines," a name suggested by Janssen.

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[5] *Philosophical Magazine*, 2, pp. 360–363, 381–382, 1833.

[6] *Philosophical Magazine*, 8, p. 391, 1836.

Many papers of this period show, however, that the distinction between emission spectra and absorption spectra was never perfectly clear until explained by Kirchhoff in 1859. This will be more readily understood when one bears in mind that all the way from Fraunhofer to Kirchhoff there were many able minds who still maintained the materiality of light.

(ii) The development of the thermopile by M. Melloni (1798–1854) of Naples during the years between 1831 and 1853. The manner in which this instrument has recently been perfected by C. V. Boys, A. H. Pfund and W. W. Coblentz has already been alluded to in Chapter XI. Our indebtedness to Melloni is mainly for his having established the identity—or, if you prefer, the parallelism—of heat rays and light rays. Melloni proved that the word *color* can be applied quite as appropriately to heat rays as to luminous rays, the property of the ray which identifies it in either case being its wavelength. The very complete transparency of rock-salt and the almost perfect absorption of lamp-black, both valuable properties to the spectroscopist, are also facts which we owe to Melloni.

(iii) The introduction of photography through the joint efforts of a large group of workers. The first man to produce a permanent picture was a French cavalry officer, Nicephore de Niepce (1765–1833) who employed in his camera a plate made sensitive to light by coating it with asphaltum. Then came the silver plate sensitized with silver iodide which is the joint product of Niepce and L. J. M. Daguerre (1789–1851), followed by a host of other more sensitive substances leading up to the silver

Macedonio Melloni (1798–1854)
Italian physicist; profound student of radiant heat

bromide emulsion now used on dry plates and films. In January of 1839, a printing paper, sensitized with silver chloride was brought out by W. H. Fox Talbot (1800–1877), a well known English classical scholar. Another important step in this series is the introduction of sodium hyposulphite as a fixing bath by the astronomer, Sir John Herschel, in February of 1840. Sensitizing baths introduced by H. W. Vogel, Sir William Abney and others extended the range of the photographic plate far into the infra red; spectrum lines were, indeed, photographed up to wavelength $\lambda = 10000$.Å.U. At the other end of the spectrum, a modest but exceedingly clever German, Victor Schumann (1841–1913) has made the photographic plate available out to the region of the longest X-rays, by dispensing with the gelatine which ordinarily supports the sensitive silver salt.

The result of all this is that the photograph has completely replaced the eye and the micrometer for accurate spectroscopic measurement.

(iv) The enunciation of Doppler's principle in 1842 and its proper interpretation by Mascart in 1848. Doppler was born in Salzburg in Austria in 1803; died at Venice in 1853. His theorem, connecting the frequency of a ray of light with the motion of the luminous source and the motion of the recipient, is a purely kinematic one and, therefore, needs only to be stated in order to be accepted, provided the underlying assumptions are realized. It is this principle which has been employed with such brilliant results by Huggins and others in getting the rate of approach, or recession of the so-called fixed stars; by Young, Dunér, Fox and others in measuring the rate of rotation of the sun; by Keeler in establishing the Maxwellian view of Saturn's rings; and by E. C. Pickering (1846–1919) in discovering a totally new class of double stars known as spectroscopic binaries. In each of these cases it is assumed that the motion of the source does not affect the frequency of the vibrating atom. If one denotes by s the speed of the source and by r that of the observer, in the line of sight, then, if the frequency of the source is n, and the speed of light c, the observed frequency N will be given by Doppler's principle, as follows:

$$N = n\left(\frac{c \pm s}{c \pm r}\right)$$

As remarked above, the principle is one which does not call for experimental verification, unless one doubts some of these basic assumptions. These presuppositions have been justified by various laboratory measures of which perhaps the best are those of Buisson and Fabry.[7]

(v) The determination of the speed of light in water. This was first done by J. B. L. Foucault (1819–1868) in 1850, and was later confirmed by Michelson, thus establishing the fact that the speed of light in different media varies inversely as the refractive index. This was the end of the corpuscular theory of light, at least in the form in which it was proposed by Newton. For an even half century following Foucault's experiment, the wave theory dominated the science of spectroscopy without a rival.

(vi) The effect of a magnetic field upon a source of light. Any account of spectroscopic activity between

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[7] *Journal de Physique*, July, 1919.

Josef Stefan (1835–1893)
Austrian physicist who discovered the fourth power law of radiation

the period of Fraunhofer and the time of Kirchhoff which did not mention Faraday's magneto-optical work would be manifestly unfair. In 1845, Faraday demonstrated the fact that the plane in which vibrations of light take place is rotated whenever the light passes, along the lines of force, through certain magnetizable bodies,[8] a fundamental discovery connecting two hitherto diverse fields of nature. In 1862, however, he tried the effect of a powerful magnetic field upon a gas flame made luminous by the addition of NaCl, LiCl, $BaCl_2$ and $SrCl_2$; and in his notebook for 12 March 1862, he reports the results as follows:

> "The colourless gas flame ascended between the poles of the magnet, and the salts of sodium, lithium, &c., were used to give colour. A Nicol's polariser was placed just before the intense magnetic field, and an analyser at the other extreme of the apparatus. Then the electro-magnet was made, and unmade, but not the slightest trace of effect on or change in the lines in the spectrum was observed in any position of polariser or analyser.
>
> "Two other pierced poles were adjusted at the magnet, the coloured flame established between them, and only that ray taken up by the optic apparatus which came to it along the axis of the poles, i.e. in the magnetic axis, or line of magnetic force. Then the electro-magnet was excited and rendered neutral, but not the slightest effect on the polarised or unpolarised ray was observed."[9]

In this brief sketch of the history of physics it has not been our practice to discuss any vain efforts or fruitless work. This experiment of Faraday's, his last serious piece of work, can hardly be reckoned as futile, in spite of its immediate negative result; for P. Zeeman distinctly asserts[10] that part of the stimulus for his search after the "effect" which goes by his name came from this vain endeavor of Faraday's. Without it we might still have been ignorant of this striking example of what Dickens calls "the universal dovetailedness of things," announced by Zeeman to the Amsterdam Academy Oct. 31, 1896.

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[8] *Experimental Researches*, vol. 3, pp. 1–26.

[9] Bence Jones, *Life of Faraday*, II, p. 449, 1870.

(vii) The perfection of spectroscopic sources. The Bunsen burner which is now in use everywhere from the kitchen to the research laboratory was first described by its inventor[11] in 1856; but seven years earlier than this Foucault made it perfectly clear that the carbon arc is an excellent source of both emission and absorption spectra; for, by passing sunlight through this arc he proved that the two bright yellow lines which appear as an impurity in the arc coincide exactly with the *D* lines of Fraunhofer; and, he then went farther and showed that on passing the continuous light of the positive crater through the flame of the arc one obtains the *D* lines reversed precisely as they are in the solar spectrum. Foucault puts the matter as follows:

> "Ainsi l'arc nous offre un milieu qui émet, pour son propre compte, les rayons D, et qui, en même temps, les absorbe lorsque ces rayons viennent d'ailleurs.
>
> "Pour faire l'expérience d'une manière plus décisive encore, j'ai projeté sur l'arc l'image réfléchie d'une des pointes incandescentes du charbon qui, comme tous les corps solides en ignition, ne donne pas de raies, et, dans ces circonstances, la raie D m'est apparue comme dans la lumière solaire."[12]

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[10] *Philosophical Magazine*, (V), 43, p. 226, 1897.

[11] *Poggendorff's Annalen*, 100, 1856.

[12] L. Foucault, *Travaux Scientifiques*, 171, Paris, 1878.

Unfortunately the full meaning and explanation of this remarkable phenomenon was not realized by Foucault and the matter was pushed no farther.

About this same time the use of the electric spark, fed by various sources of E. M. F. and shunted with a condenser, was introduced by another Frenchman, A. P. Masson (1806–1860).[13]

In 1854–1855, Dr. David Alter, a practising physician in Freeport, Pennsylvania, used the spark to map the spectra of eleven different elements, all metals. Two brief papers in volumes 18 and 19 of the *American Journal of Science*, Second Series, describe his work and reproduce his sketch.

Here also belongs the characteristic spectrum of the hydrocarbon flame, first described by William Swan to the Royal Society of Edinburgh in 1856, and since known as the *Swan Spectrum*. It is worth noting also that the collimator of the spectroscope was introduced by Swan in 1847. It was not long after this until observers of spark spectra noticed certain groups of lines as common to the spectra of all metals. These are the so-called *air lines* which owe their existence to the presence of oxygen and nitrogen in the immediate neighborhood of the electrodes. In the late fifties, J. Plücker (1801–1868) the distinguished geometer and professor of physics at the University of Bonn, brought out the vacuum tube which goes by his name and which confines the discharge to a narrow capillary, thus enabling one to study the spectrum of a gas without being bothered by lines which come from the electrodes. Although the best work of A. J. Ångstrom

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[13] *Annales de Chimie et de Physique*, (3), **31**, pp. 295–326, 1851.

(1814–1874) comes after the time of Kirchhoff and Bunsen, he nevertheless pointed out, in the fifties, that a great many of the metallic lines make their appearance only in the immediate vicinity of the poles.

(viii) The mathematical consequences of the wave theory of light. The laboratory tools of spectroscopy were, in a certain limited and superficial sense, completed by the seven advances which have just been mentioned. In addition to this, the mathematical theory initiated by Fresnel was, if not perfected, brought up to the point where it covered all ordinary cases of diffraction. The two outstanding achievements in this line, between the time of Fraunhofer and that of Kirchhoff are the book on *Diffraction Phenomena* by F. M. Schwerd (1792–1871) published at Mannheim in 1835, and the powerful memoir of Sir George Stokes (1819–1903) on the *Dynamical Theory of Diffraction* read before the Cambridge Philosophical Society in 1849. Schwerd discusses very fully the kinematic consequences of the wave-theory; but Stokes bases his work upon the elastic properties of the medium and thence proceeds to determine the law of disturbance in one of Huygens' secondary waves of light. This having been done, the rest is what Stokes calls "a mere matter of integration," that is the summation of the effects of all the elements which go to make up the diffracting aperture.

THE ERA OF KIRCHHOFF AND BUNSEN

This hasty and imperfect survey of four decades brings us up to the work which the two Heidelberg professors accomplished in 1859. Their whole story is told with

GUSTAV ROBERT KIRCHHOFF (1824–1887)
Established the law which goes by his name and thus laid the foundation of modern spectroscopy

completeness and rare clearness in four brief papers by Kirchhoff.[14] *Gesammelte Abhandlungen* pp. 564–625 (Barth: Leipzig, 1882). In this same volume, immediately following these four papers, is a brief *History of Spectrum Analysis* by Kirchhoff which will be found very illuminating by everyone who desires to get a correct perspective of the work of Ångstrom, Stokes, Stewart, and other investigators of this period.

The essential contribution of Kirchhoff's first paper[15] is a repetition and generalization of the results obtained by Foucault in reversing the sodium *D* lines. From these he concludes that colored flames which of themselves give bright sharp lines will, when they are placed in front of a source of sufficient intensity, absorb light of precisely the same wavelength as that of these bright lines; and will thus introduce dark lines in their stead. He infers also that the Fraunhofer lines, excepting those which owe their origin to the earth's atmosphere, are produced by the presence, in an incandescent solar atmosphere, of precisely those elements which, in the flame, give rise to lines of the same wavelength. Here in germ at least, is Kirchhoff's law expressing the relation between emission and absorption—a relation arrived at within twenty-four hours after his seeing the Fraunhofer lines artificially produced.

In his second paper, presented to the Berlin Academy in December, 1859, Kirchhoff proceeds to a more rigid demonstration of his law. The proof is based upon the three following fundamental ideas:

(a) The first is that a body which is in a region of constant temperature and has attained thermal equilibrium emits heat at the same rate at which it receives it.

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[14] *Gesammelte Abhandlungen*, pp. 564–625, Barth, Leipzig, 1882.

[15] *Gesammelte Abhandlungen*, p. 564.

(b) Secondly, the assumption is made that the energy radiated by any body is radiated entirely at the expense of its own heat; and that whatever energy is absorbed by a body is transformed into heat only and not into any other form of energy.

(c) The third is the idea of a perfectly black body, that is, one which is capable of absorbing rays of all wavelengths and reflecting none. Such a body, at that time, existed only in the imagination of Kirchhoff and was first realized in the laboratory by W. Wien and O. Lummer.[16]

Building upon this foundation and the ordinary definitions of absorption and emissive power, Kirchhoff shows, with less than a page of simple algebra, that, for any body whatever the ratio of its emissive power to its absorption for any particular wavelength at any particular temperature is the same as the corresponding ratio for a black body. Or if e denotes the emissive power of any given body and a its absorption; E the emissive power of a black body and A its absorption, then Kirchhoff's law crystallizes into the following form:

$$\frac{e}{a} = \frac{E}{A}$$

It will be readily understood that, for a black body, A is always unity and E/A is a function of the temperature of the body. Hence the ratio e/a, numerically equal to E, is, for any given temperature, a definite and constant ratio.

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[16] *Wiedemann's Annalen*, 56, p. 453, 1895.

The third paper is a still more rigid demonstration of this result. Various other proofs of Kirchhoff's law have been given, notably that by E. Pringsheim in *Rapports au Congrès de Physique*, 2, pp. 100–132, 1900. Chapter XV of O. W. Richardson's *Electron Theory of Matter* is largely devoted to this subject. A briefer demonstration is to be found in Bligh's *Quantum Theory*, pp. 15–18, Longmans, 1926.

The general principle thus rigidly established explains not only the reversal of the *D* lines observed by Foucault and later by Kirchhoff but also a host of ordinary phenomena, such as one observes on looking into a heated furnace where there may be pieces of iron, glass, and other objects besides red-hot coals. It is almost impossible to tell them apart. The glass, for example, *transmits* from hot coal the very rays which it alone is unable to *emit;* and it emits precisely those rays which glass absorbs. The consequence is that the glass presents to the eye almost the same appearance as the iron; and each resembles the hot coal.

Kirchhoff thus made it perfectly clear once for all that opaque bodies, such as a copper wire, will glow at a moderate temperature while transparent bodies, such as gases, must be heated to vastly higher temperature; and when a heated gas gives a bright line spectrum, its only possibilities in the way of absorption are at those particular wavelengths which it emits. Here we have a law which holds not only for every particular wavelength, but also for every particular kind of absorbing and emitting mechanism, including molecules, atoms, and free electrons.

The force of Kirchhoff's argument lies in the fact that he proved that this relation between absorption and radiation *must* be so if the assumptions upon which he starts are justifiable. Other observers, such as Herschel Swan, Stokes, Balfour Stewart and others, rendered the principle highly probable and deserve credit accordingly; but Kirchhoff clinched the matter, and thus established the science of spectroscopy upon a firm foundation.

In the fourth paper of this series, Kirchhoff and Bunsen jointly establish the fact that, in the spectrum of any element, the position of any bright line is, within the limits of errors of observation, independent of the temperature of the source, independent of the kind of flame, arc, or spark which produces the line, and independent of any other elements with which it may be chemically combined.

Taken altogether these papers form an excellent illustration of good scientific method which, in physics, ordinarily involves the five following steps:

(i) The establishment of the experimental facts.

(ii) The proper pigeon-holing of the facts; i.e., their allocation with other facts of essentially the same kind.

(iii) The impersonalization of the facts; i.e., elimination of the observer's subjective self.

(iv) The formulation of the facts; i.e., their expression, if possible, in the form of a physical law.

(v) The prediction of new facts.

This fifth step is taken in the latter part of the present paper where the possibility of discovering new elements and of determining the composition of the fixed stars is pointed out. The actual discovery of Caesium and Rubidium through the appearance of new spectral lines, is announced in a closely following paper, by these same men.[17] It was within the next two decades that three other new elements, Thallium, Indium, and Gallium were discovered by the spectroscope. The rôle of this same instrument, used by Lord Rayleigh and Professor Ramsay in identifying the noble gases, Helium, Neon, Argon, Krypton, and Xenon, is still fresh in the minds of the present generation.

One's admiration for these early researches cannot fail to increase when he remembers that most of the observations, during these first two decades, were made through a single prism of glass or carbon-bisulphide. Kirchhoff used four prisms in series; Huggins, six of 45 degrees each. Sunlight was almost the only source which would permit the use of a train of prisms. A still further handicap was the complete absence of any well established scale of reference such as we have today in the iron spectrum and in other standard wavelengths. Better instruments fitted with Nobert gratings began to appear in the early sixties and were used by Mascart, Ångstrom and others for wavelength determinations; but even the best of the Nobert gratings would today rank as practically worthless. The superiority of the Rutherfurd gratings, the first of which were being ruled about this time, was at once recognized by Professor C. A. Young and others.

We may now consider the science of spectroscopy firmly established upon the general principle that *any body emits those radiations which it absorbs, provided these radiations are also emitted by a black body at the same temperature.* The reader who is interested in the recent modifications of this law and the deviations from the assumptions which underlie it will find these problems discussed with great acumen and at length by A. Cotton.[18]

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[17] *Poggendorff's Annalen,* **113**, p. 337, 1861.

The interest awakened by the two Heidelberg scholars spread rapidly through the entire field of astronomy, physics, and chemistry. Kirchhoff himself completed a map of the solar spectrum drawn on an arbitrary but generous scale in which he identified a large number of the lines and indicated on the map the element in which each of these lines had its source. Some of the older spectroscopists of the present generation still recognize certain of Kirchhoff's numbers, e.g., the chromospheric line λ 5317 as "1474 of Kirchhoff."

ASTROPHYSICS—HUGGINS, YOUNG AND DUNÉR

One of the first men to use this novel and powerful scientific method was the late Sir William Huggins of London who seized eagerly upon it to discover the constitution of comets, nebulae, and new stars, as well as of the sun and fixed stars. By 1868, he had sufficiently mastered the difficult technique of using a spectroscope attached to the eye end of a telescope to measure the speed of recession of the star, *Sirius*, estimating it at 29.4 miles an hour.[19]

Huggins was immediately followed by C. A. Young of Princeton who, at the Spanish eclipse of 1870, adjusted his spectroscope so carefully upon the limb of the sun that just at the instant of inner contact of the limb of the moon with that of the sun a series of brilliantly colored

[18] *Astrophysical Journal*, 9, pp. 237–268, 1899.

[19] *Philosophical Transactions*, **158**, p. 529, 1868.

lines flashed out through the entire length of the spectrum. The dark lines of Fraunhofer were suddenly *reversed* as Young had expected from the theory of Kirchhoff. This *flash spectrum* has since then been observed and photographed at numerous eclipses, in spite of the fact that its duration covers only a second or so of time.

More recently N. C. Dunér, J. E. Keeler, W. W. Campbell, Philip Fox, C. E. St. John and others have employed this method to obtain exceedingly accurate values for the rotation-period of the sun and other motions in the line of sight. Few experiments in the entire history of science combine as much skill and exquisite theory as the photographic spectra by which Keeler[20] proved that Saturn's rings have precisely the meteoric structure assigned to them by Maxwell's dynamical theory.

Our nearest star, the sun, has deservedly received more attention than any other. It was, however, nearly half a century after the time of Fraunhofer that his solar lines were mapped and described in terms of their wavelengths. This was first done in 1868 by A. J. Ångstrom (1814–1874), professor of physics in Upsala. On his atlas, the solar lines are drawn to a uniform scale, such that a distance of one millimeter between any two lines means a difference of one unit in their wavelengths. A spectrum plotted in this way is said to be *normal*. The unit in which the Swedish physicist expressed his wavelengths—10^{-8} cm. —proved so convenient that it has been adopted by the spectroscopists of all nations, has been redefined by the International Solar Union at Paris in 1907 as 1/6438.4696 part of the wavelength of the red cadmium ray and is now universally known as the "ångstrom." This amounts, of course, to the adoption of the wavelength of the red cadmium line as an arbitrary unit of length, independent of the metric system and thus realizes the dream which Maxwell playfully expressed by saying that those who expected their writings to be more permanent than the earth, the base of the metric system, should measure lengths in terms of a wavelength of sodium light.[21]

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[20] *Astrophysical Journal*, **1**, p. 416, 1895.

Another of the early spectroscopic results was the discovery by Plücker and Hittorf[22] that gases exhibit different spectra, depending upon the manner in which they are excited. These men introduced the important distinction between band spectra and line spectra—first-and second-order spectra were the names they used—a distinction, as we now interpret it, between the spectra of molecules and the spectra of atoms.

Before leaving the period of Kirchhoff and Bunsen, it ought to be remarked that each of these men was eminently successful as a teacher and that each of them endeared himself to a large number of students. Bunsen, whose name has become a household word, first through his invention of a good battery and afterwards (1856) by his invention of the burner which goes by his name, always remained at Heidelberg where many stories still linger concerning his vigorous and striking personality. Immediately after the close of the Franco-Prussian war the Prussian government left no stone unturned to make

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[21] Maxwell, *Treatise on Electricity and Magnetism*, third edition, I, p. 3.

[22] *Philosophical Transactions*, 155, pp. 1–29, 1865.

Henry Augustus Rowland (1848–1901)

Established the magnetic effect of an electric charge in motion; and thus laid the foundation of the electron theory; inventor of the curved grating

the University of Berlin the center of German science and, with this in mind, invited Kirchhoff and Helmholtz to join that outstanding group of scholars. Here, besides a host of German students, men such as Karl Pearson and Sir Arthur Schuster of England, Magie, Pupin, Webster and Ames from America listened to Kirchhoff's lectures on mathematical physics, a course which was given each year up to the time of his death in 1887.

THE ERA OF ROWLAND

The celebrated remark of Clerk Maxwell that the whole of modern science is an answer to the question *How much?* received a superb illustration in the decade following the year 1882. For it was in this year that Professor Henry A. Rowland (1848–1901) of Johns Hopkins University succeeded in making a diffraction grating so perfect as to secure an accuracy in spectroscopic measurements about one hundred times greater than that of Ångstrom whose solar atlas had furnished the accepted standards of wavelength during the previous decade.

It was early recognized by Rowland, Kayser, Rayleigh and others that, if we are ever to learn much about the structure of atoms and molecules, this information is likely to come from the spectra of the elements and that the spectra of the elements can be understood only by discovering some kind of order in their arrangement. It was precisely this last discovery which the new methods of Rowland made possible. In fact, his numerous and exact answers to the question *How much?* ushered in a new era in the study of light.

The concave grating

Rowland became interested in the subject of phosphorescence where he needed to use different spectral colors, and soon realized that neither of the two available means, a glass prism or a Rutherfurd grating, was competent to give the spectral purity which he desired.

L. M. Rutherfurd (1816–1892) was a gentleman living in New York City who had abandoned the practice of law in order to give his time to astrophysics. His own work and that of Professor Young at Princeton soon showed that Rutherfurd's gratings were vastly superior to those of the German mechanician, Nobert. Rowland, however, needed something better still and recognized at once that the quality of a grating could never surpass that of the screw by which it was ruled. He was a man of extraordinary manipulative skill, as was already evident from his Berlin experiment; and therefore never hesitated when it came to making a perfect screw and mounting it in a ruling engine which would lay the furrows of a diamond point side by side with a spacing of only $\frac{1}{15,000}$ inch and with an error which at no point exceeded $\frac{1}{100,000}$ inch. The screw was about an inch in diameter and was cut with something like fourteen threads to the inch. The ruled space on some gratings covered a length of six inches, the furrows reaching a length of four inches. To rule a grating of this size the engine had to run automatically for no less than four days and nights.

Up to 1882, all gratings had been ruled upon flat surfaces; but in this year, Rowland hit upon the brilliant idea of ruling a grating upon a concave spherical surface—

Lewis Morris Rutherfurd (1816-1892)
Lawyer and amateur spectroscopist; ruled the finest diffraction gratings before the period of Rowland

upon the mirror of a reflecting telescope, indeed—and he thus eliminated at once the collimator and telescope of the ordinary spectroscope. The simplicity of the device was at once evident to everyone; for the entire instrument consists of only a slit, a grating and a photographic plate. Another striking merit is its property of bringing all orders of spectra to the same focus, so that overlapping orders may be employed for the rapid and accurate determination of relative wavelengths. If one uses an eyepiece instead of a photographic plate he sees the red of the second order shining through the dark Fraunhofer spaces in the blue of the third order.

The fact at once emerged that the solar map and wavelengths of Ångström and Thalen would no longer suffice. Rowland, therefore, with clear vision undertook the preparation of a photographic atlas of the solar spectrum and the measurement and identification of no less than 15,000 Fraunhofer lines, an appalling task which was to consume the best part of his energies for the next fifteen years. It was clear that the value of this work would be greatly enhanced if all these wavelengths, whose relative accuracy was sure to be of high order, could be referred to some one line whose wavelength had a better known value than any hitherto existing. Dr. Louis Bell spent two years of skillful and careful work upon this problem and arrived at a value for the sodium D_1 line to which Rowland gave a weight equivalent to that of the four best previous measures.[23] It was thus that the value λ 5896.156 A. U. came to serve as the base of Rowland's Preliminary Table of Solar Spectrum Wavelengths, published in the *Astrophysical Journal*, volumes 1–6, (1895–1897). The accuracy of Bell's value was estimated at that time as 1 in 100,000. The interferometer method, devised by Professor Michelson, showed, however, within three or four years that Bell's value was affected by an error of at least one part in 30,000.

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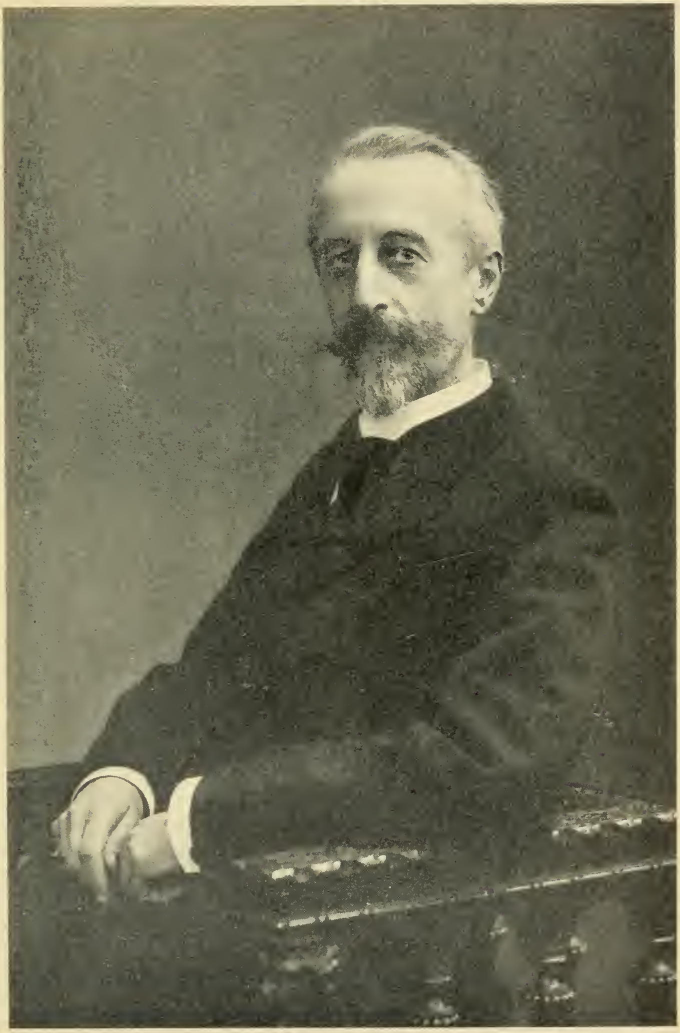
[23] *Philosophical Magazine*, July, 1893.

The year 1888 saw the completion of Rowland's solar map, a superb photograph extending from Fraunhofer's B to the extreme ultra-violet of the sunlight which is able to penetrate our atmosphere; roughly from λ 7000 to λ3000 Å. The scale is such that there are only between eight and nine ångstroms to the inch, so that the entire length of the map is something over thirty-five feet. The identification of the lines on this spectrum was a gigantic task involving the examination of every element then known, save *Gallium* of which no specimen was available at the time. The completion of the work, however, placed the science of spectroscopy upon a new and higher plane.

SPECTRAL-SERIES

The solar spectrum, being an integral of the spectra of all the elements, presents to the eye not the slightest trace of regularity. Almost as disorderly and haphazard is the arrangement of the lines in the spectrum of Iron, Titanium, and many other elements; and yet in some of the elements, notably Zinc, Cadmium, and Magnesium, traces of order were early observed. Certain pairs and triplets were found to repeat themselves.

The first series of lines to be established was in the vacuum-tube spectrum of Hydrogen where, in 1885, J.



HEINRICH G. J. KAYSER (BORN 1853)
Eminent German spectroscopist and inspiring teacher

J. Balmer[24] of Basel succeeded in accurately describing the position of the hydrogen lines by the following simple, but purely empirical, formula, for the wavelength, λ.

$$\lambda = h \frac{m^2}{m^2 - 2^2}$$

where h is a constant having the value 3645.6, and m represents the natural numbers beginning with 3. With better values for the wavelengths and a slightly different value for h, this series represents the facts of the case with extraordinary accuracy.[25]

Almost immediately after this work of Balmer's, Kayser and Runge then at the Technische Hochschule of Hannover began their search for series in the spectra of other elements. They immediately realized the necessity for more accurate wavelengths and courageously set about making the measures; and wisely directed their first efforts to the spectrum of iron, the lines of which were to be used as standards of comparison. Their tables of wavelengths were accompanied by an atlas of the iron spectrum on the sçale of one millimeter to the ångstrom. The whole map was published by the Berlin Academy in 1888. Its accuracy, so far as regards relative wavelengths, is quite up to the standard set by the authors, which was one-tenth of an ångstrom.

Kayser and Runge then used the concave grating to secure a list of wavelengths for a large number of elements and discovered from these tables many series of lines, satisfying a formula of the general type:

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[24] *Wiedemann's Annalen*, 25, pp. 80–87, 1885.

[25] J. S. Ames, *Philosophical Magazine*, 30, p. 55, 1890.

$$\frac{1}{\lambda} = A + \frac{B}{m^2} + \frac{C}{m^4}$$

where, as before, m represents the natural numbers, beginning with 3, and A, B, and C are constants. Balmer's formula is a special case of Kayser and Runge's, where $A = \frac{1}{h}$, $B = -4A$ and $C = 0$. The impetus which these two single-minded and clear-minded investigators gave to spectral research in all parts of the world is something which can be fully realized only by the generation which has felt it.

A few years later, J. R. Rydberg of the University of Lund made a great stride by introducing the idea of wave numbers, by devising a better series formula, and by discovering a number of important relations between spectral series. All of these he describes in a noteworthy paper of only seven pages.[26] Here he adopts the three natural "groups" of lines, already employed by Liveing and Dewar, and accordingly classifies his series under three heads, namely:

(i) *Principal*, including lines of greatest intensity.
(ii) *Diffuse*, including lines of intermediate intensity.
(iii) *Sharp*, including the weak lines.

Some years later a fourth group of series was discovered by Arno Bergmann of Jena who showed[27] that this new

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[26] *Philosophical Magazine*, 29, pp. 331–337, 1890.

[27] *Zeitschrift für Wissenschaftliche Photographie*, 6, pp. 113–130, pp. 145–169, 1908.

Carl Runge (1856–1927)

Master of spectroscopic theory; late Professor of Mathematics in the University of Göttingen

series—now known as the Bergmann series—has many properties strikingly different from those of the other three groups.

The formula employed by Rydberg to describe the several series which he found in each of the three groups is the following:

$$\text{Wave number} = \frac{10^8}{\lambda} = n = n_0 - \frac{N}{(m+\mu)^2}$$

where n is the number of wavelengths in one centimeter, m is any positive integer, n_0 and μ are constants peculiar to the series, and N a constant common to all series and to all elements. The sequel showed that N is indeed a universal constant which has the approximate value 109675. Each different series in the diffuse group is characterized by its own n_0 which is known as the *limit* of the series; so also, in the sharp group each series has a different limit. These two groups are distinguished from each other by characteristic values of μ. The best account of Rydberg's work is perhaps found in the report which he made to the congress of physicists held at Paris in connection with the World's Fair in 1900.[28] For this purely descriptive expression, Rydberg claimed no kinematic or dynamical basis whatever. It proved itself surprisingly competent but defied explanation for nearly a quarter of a century. To this we shall return presently.

A DIGRESSION ON THE PRESSURE-SHIFT

In 1895, Humphreys and Mohler examined the emission spectra of various arcs when worked under considerable pressure and found that the spectral lines were invariably shifted towards the red end of the spectrum and that the amount of the shift is directly proportional to the wavelength and to the excess of the pressure above one atmosphere.[29] This pressure-shift appeared as a new and disturbing factor upon the spectroscopic horizon. The amount of the shift varies from one element to another; and this fact alone rendered it highly probable that the Fraunhofer lines do not possess that constancy of wavelength which would fit them for terrestrial standards. The feeling at the time was well expressed by the late Professor Carl Runge of Göttingen when, at a conference held at the Yerkes Observatory in 1897, he rose to discuss a paper on pressure-shift by Dr. Humphreys and opened his remarks with the following sentence: "Mr. Chairman, Nature is getting more and more disorderly every day." The speaker doubtless had in mind also another bit of "disorder" which Zeeman had recently introduced and which has been mentioned above. Messrs. St. John and Ware, working at Pasadena and independently at Mount Wilson,[30] found the pressure shift very different for different lines and something which must be taken into account even for the change of altitude between Mount Wilson and the valley below.

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[28] *Congrès International de Physique*, vol. 2, pp. 200–224, Paris, 1900.

MICHELSON'S ESTABLISHMENT OF THE RED CADMIUM WAVELENGTH

If we return from this digression and take account of stock at the end of the nineteenth century, we shall find

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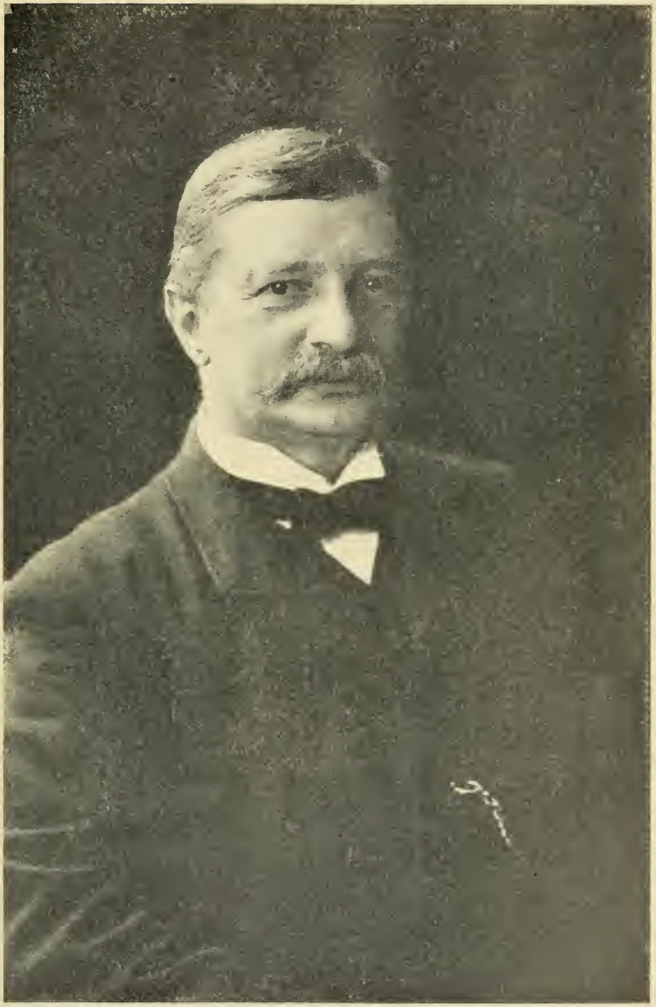
[29] *Astrophysical Journal*, 3, pp. 114–137, 1896.

[30] *Astrophysical Journal*, 36, p. 14, 1912.



JOHANNES R. RYDBERG (1854-1919)
Swedish physicist; first to describe with accuracy and simplicity the distribution of lines in spectra

that a large proportion of all the elements in the periodic table had been examined and in the case of the first three columns, a large proportion of the lines had fallen into series as described by the formulae of Rydberg, Kayser, Runge, Ritz, and others. Wavelengths the world over were expressed in terms of Rowland's *Tables;* everyone had confidence in the relative values there given; but it is only fair to say that there had always been uncertainty, even in the mind of Rowland himself, as to the absolute value of the sodium D_1 line upon which the whole system was established. This uncertainty was changed into certainty in 1893. For in 1892, Professor A. A. Michelson, then of Clark University, was invited to Paris to measure the standard metre in terms of the wavelength of light, by use of his interferometer. Professor F. L. O. Wadsworth went with him to assist, and M. Benoit, then Director of the International Bureau of Weights and Measures, where the work was done, was also associated with them. The interferometer method has the advantage of eliminating all measurement of angles and of allowing one to produce an exact multiple of a given distance between two plane mirrors. With a set of nine intermediate standard distances of this kind, Michelson succeeded in evaluating the meter with an extraordinary degree of accuracy. The details would here be out of place. Michelson's own account will be found in his *Light Waves and Their Uses* (University of Chicago Press, 1903) also in *Travaux et Mémoires*, XI (1893) of the International Bureau of Weights and Measures.

The result of this experiment, executed with rare skill, was that Michelson found the length of the meter, at

15°C. and 760 mm., to be equal to 1553163.5 waves of the red cadmium ray; or in other words, one wavelength of this red ray is 6438.4722 ångstrom units, which when reduced to dry air, gives 6438.4700. The largest error to be expected in this result was one part in two million; but the chances are that the accuracy is really much higher than this; for when in 1907 an independent determination was made by Messrs. Benoit, Fabry, and Perot, they obtained for the red cadmium ray in dry air the value $\lambda = 6438.4696$ which differs from Michelson's corrected value by only one part in 16,000,000.[31] Michelson's measures made it highly probable that Rowland's wavelengths were all too large by about one part in 30,000. Later measures by Perot and Fabry confirmed the result of Michelson and showed, in addition, that even the relative wavelengths of Rowland were subject to errors as great as one part in 100,000.[32] In the meantime, Mr. L. E. Jewell, then at Johns Hopkins University, had published his observations on the want of exact coincidence between solar and corresponding metallic lines showing not only that solar lines are displaced in general toward the red, but that the different lines of one and the same element are *differently displaced.* The effect of Jewell's work[33] was to depose the solar lines from the high commanding position which they had occupied since the publication of Rowland's tables.

Among the noteworthy events of the International Congress of Arts and Science, held on the occasion of the

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[31] *Travaux et Mémoires,* 15, p. 131, 1913.

[32] *Astrophysical Journal,* 15, p. 272, 1902.

[33] *Astrophysical Journal,* 3, p. 89, 1896.

World's Fair at St. Louis in 1904, was the establishment of the International Union for Cooperation in Solar Research. One session of the first meeting was devoted to the question of a new system of standard wavelenths. The need for revision was reluctantly but generally admitted. It was clear that such a system must be based upon Michelson's value for the red cadmium ray, that artificial sources must be used and that the work must be proceeded with at once. In 1907, the International Union held its third congress in Paris and listened to the report of Benoit, Fabry, and Perot upon the evaluation of the standard meter in terms of the red cadmium ray.[34] The striking agreement—practical coincidence—of the value here reported with that obtained by Michelson some thirteen years earlier left no doubt as to the wisdom of adopting the following resolution:

> "La longueur d'onde de la raie rouge de la lumière du Cadmium produite par un tube à électrodes est 6438.4696 Angström, dans l'air sec à 15° du thermomètre à hydrogène, à la pression de 760 mm. de mercure, la valeur de g. étant 980.67 (45°). Ce nombre sert de définition à l'unité de longueur d'onde."

The primary standard of wavelength having thus been agreed to, the next problem was, of course, to measure in terms of the International Ångstrom a number of secondary standards scattered throughout the length of the arc spectrum of iron. In 1910, the International Union held its fourth conference at Pasadena and adopted as secondary standards some 49 lines, each of which had been independently measured by Fabry and Buisson in France, by Eversheim in Germany and by Pfund in America. For each line the mean value of these three determinations was adopted.[35]

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[34] *Transactions I. U. S. R.*, 2, pp. 109–137, Manchester, 1908.

By the work of K. Burns and others this first list of secondary lines was nearly doubled so that practically 100 lines in the standard artificial source—the iron arc—were soon known with a precision of 0.001 ångstrom, or one part in five million. Here the limit of accuracy appears to have been reached. At least so many slight "effects," depending upon the various physical conditions under which the line is produced, make their appearance that secondary standards are still (1927) given only to the third decimal of an ångstrom. Indeed, it was one of the earliest observations in spectroscopy that lines in the spectrum have a width and character peculiar to each individual line.

This system of international wavelengths was completed (?) by setting up a list of tertiary standards, that is to say, a set of iron lines which had been interpolated between the secondary standards.[36]

Upon this foundation of primary, secondary and tertiary standards are based a host of excellent measures upon nearly all the elements of the periodic table. These are all answers to the question *How much?*, and the wavelengths of the elements thus accurately determined have been exceedingly useful as criteria in deciding between various theories as to the structure of matter.

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[35] *Transactions I. U. S. R.*, 3, p. 139, Manchester, 1911.

[36] For these values, see Keivin Burns. *Lick Observatory Bulletin*, No. 247, 1913; Burns, Meggers, and Merrill, *Scientific Papers of the Bureau of Standards*, No. 274, 1916; and Buisson and Fabry, *Journal de Physique*, October, 1921.

THE INFRA-RED SPECTRUM

That part of the spectrum which lies in the infra-red beyond the range of the photographic plate was first accurately investigated by S. P. Langley (1834–1906), who in 1881 perfected a radiation balance which he called a *bolometer*, really a Wheatstone bridge of extreme sensitivity, for measuring differences of temperature. With this instrument he succeeded in mapping no less than 700 dark lines in the solar spectrum between Fraunhofer's A and wavelength 53,000 ångstroms, i.e., between 0.76 μ and 5.3 μ where μ denotes a micron, that is, a thousandth of a millimeter. Toward the end of the century, Rubens, Paschen, Nichols, Wood, and von Beyer perfected several new and exceedingly clever methods of isolating and measuring these long heat rays so that, by 1911, rays having a wavelength of more than one-third of a millimeter (342 μ) had been mapped.

In the meantime, electric oscillators of smaller and smaller dimensions had been employed to produce electromagnetic waves, until in 1920 W. Möbius[37] was able to measure Hertzian waves as short as seven millimeters. The gap which separated the ends of the optical and the Hertzian spectra consisted of less than five octaves; i.e., the distance between heat waves one-third millimeter long and electric waves seven millimeters long. It was clearly seen by E. F. Nichols and J. D. Tear that this gap might be closed either by extending the electric waves to *shorter* lengths or by extending the heat rays to *longer* lengths; they chose to do it by *both* methods. The long wave radiation of the mercury arc was isolated by the use of appropriate absorbents, and the wavelengths of these infra-red heat rays were measured by means of a Fabry and Perot interferometer. In this manner the infra-red spectrum was extended to 420 μ.

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[37] *Annalen der Physik*, 62, p. 293.

The electromagnetic waves were produced by minute Hertzian oscillators only a fraction of a millimeter in length, resonators which emitted a fundamental wave length of less than two millimeters and a strong harmonic of only 0.22 mm. Here the wavelengths were measured by three different methods—the Fabry and Perot interferometer, a pair of Boltzmann mirrors, and the reflecting echelon. The result was that these two observers not only closed the gap between the electric and thermal sides of the spectrum, but followed each of these two types of radiation until they overlapped by as much as an octave.[38]

This difficult and cleverly executed piece of research will always be associated with the opening session of the National Adademy of Sciences in its splendid new building in Washington. For it was on this occasion, April 29, 1924, that Professor E. F. Nichols was describing this work to a large and attentive audience and had nearly completed his presentation of the matter when he paused, quietly sank into a seat, and immediately passed away. The paper which he was reading at the time, together with an inspiring sketch of his life and work by Professor Fox, are to be found in the *Astrophysical Journal*, **61**, 1–37, 1925.

[38] They describe their work in two papers, the earlier of which is found in the *Physical Review*, **21**, 587, 1923; the later, in the *Astrophysical Journal*, **61**, 17, 1925.

X-RAY SPECTRA

We must now pass to the other end of the spectrum, the region of extremely short wavelengths.

It was in a translation of a German communication[39] that the outstanding discovery of W. C. Röntgen (1845–1923) was announced to English-speaking people. Here he described in a clear, simple, modest, and thoroughly scientific manner a new and invisible radiation which has the remarkable property of penetrating many bodies opaque to ordinary light rays. This discovery, like all other discoveries of the first order, was fraught with many important consequences never suspected when first made known. Its importance in medicine was commented upon by Röntgen in his first public announcement, made to the Physico-Medical Society of Würzburg in November, 1895; but the nature of the radiation remained a puzzle for nearly twenty years. From the very start, it was clear that the source of these X-rays was a target bombarded by cathode rays; but what happened at this target was a mystery. The nearest guess at the true explanation was doubtless that of Sir George Stokes who suggested, as early as 1897, that X-rays are electromagnetic pulses produced by the sudden stoppage of the negatively charged particles—electrons we now call them—which constitute the cathode ray. In 1899, Haga and Wind of Groningen,[40] by passing a beam of X-rays through a narrow slit and observing a slight widening of the image, rendered it probable that these rays consist of waves some five thousand times shorter than those of the red cadmium ray. This result, however, was too surprising to win acceptance, especially since it was impossible to produce regular reflection of these rays.

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[39] *Nature*, 53, p. 274, 1896.

[40] *Wiedemann's Annalen*, 68, p. 884.

The problem was solved, however, in 1912 when Professor Max Laue, then at the University of Zürich, realized that while it was impossible to rule a grating fine enough to measurably diffract waves as short as those proposed by Haga and Wind, it was possible that nature had already provided just such gratings. Laue suggested that the spacing of the atoms in a crystal might be regular enough and close enough to diffract even waves that are not more than one ångstrom in length. His suggestion was put to the experimental test by Friedrich and Knipping,[41] who found that a pencil of X-rays when passed symmetrically through a small crystal was deviated in different directions through large angles, agreeing closely with the predictions of Laue. The crystal consisting of three sets of parallel planes, each set intersecting the other two, acted as a three-dimensional diffraction grating and performed the function of the dispersion piece in an ordinary spectrometer. It was clearly recognized that before such a space-lattice could be used to measure the wavelength of an X-ray, it would be necessary to discover the distance apart of the diffracting planes in the crystal, a feat first accomplished by W. L. Bragg, *Proc. Roy. Soc.* A. **89,** 248 (1913). What Bragg found from a profound study of certain halogen salts belonging to the cubic system was the fact that, in the case of rock salt, the mass associated with each elementary cube in the crystal is one-half of the molecule, NaCl. The rest of the task was comparatively easy, because the mass of a hydrogen atom had already been determined with a high degree of accuracy to be 1.663×10^{-24} grams; and, the mass of the hydrogen atom being known, the mass of the sodium and chlorine atoms were obtained by multiplying by their respective atomic weights. Thus the mass of the elementary cube of rock salt became $1/2(23 + 35.5)\ (1.663 \times 10^{-24})$ grams. The next step was to obtain the *volume* of the elementary cube from the known density of the salt crystal, 2.15, by use of the equation

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[41] *Annalen der Physik*, **41,** p. 971, 1913.

$$\text{Mass} = \text{Density} \times \text{Volume}$$

or

$$1/2(23 + 35.5)\ (1.663 \times 10^{-24}) = 2.15 \times d^3$$

where d is the length of one side of an elementary cube measured in centimeters. From this equation Bragg found the value of d, the distance separating the elementary planes of rock salt, to be of the order of 2.8×10^{-8} centimeters. With this information in hand, he employed a method very similar to that of ordinary optical spectroscopy for measuring the wavelengths of various X-rays. His laboratory equation was

$$2d \sin \theta = n\,\lambda$$

where θ is the angle between the incident ray and the diffracting plane.

Siegbahn and others have recently improved the X-ray spectrometer to the point where relative wavelengths can be measured with an accuracy of one part in ten thousand.

X-ray spectra given by the different elements were soon found to contain not only a general radiation, giving a continuous spectrum, but also a characteristic radiation consisting mainly of two lines called "K" and "L". The characteristic X-ray spectrum is thus much simpler than the corresponding optical spectrum. The range of wavelengths covered by X-rays may be illustrated by saying that in the case of the K_α line they extend from $\lambda = 0.203$ ångstroms for tungsten up to $\lambda = 11.95$ ångstroms for sodium. From a study of the rays emitted by radioactive substances has emerged a series of still shorter wavelengths ranging from 0.01 to 1.4 ångstroms. The discovery made by H. G. J. Moseley (1887–1915),[43] that the frequency represented by either of these two lines is related in a very simple way to a certain number, now called the *atomic number*, which defines the physical and chemical properties of that element, must always rank as one of the high achievements of the human mind. The relation between the frequency, ν, and the atomic number N is as follows:

$$\nu = a(N - b)^2$$

where a and b are constants for either particular line. In this discovery of Moseley, where he has assigned to each element a characteristic integer, he has probably laid the foundation of a more accurate chemical theory than was hitherto possible. Students of physics will always associate with his discovery the tragic circumstances of the year following its announcement. Moseley was in Australia with the British Association when the war broke out; but he returned to England, enlisted in the Royal Engineers and was killed on the Gallipoli peninsula on August 10, 1915.

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[43] *Philosophical Magazine*, 27, p. 703, 1914.

We may now consider the electromagnetic spectrum as actually observed and mapped in the laboratory, throughout some fifty octaves, that is from a wavelength of 0.01 ångstrom up to 5000 kilometers. If any gap still (1927) exists, it is only in the region between 100 ångstroms and 10 ångstroms where the wavelengths are too short for ordinary artificial gratings and too long for natural crystal gratings.

THE RADIATING ATOM

At the beginning of this chapter, the fourfold purpose of the science of spectroscopy was outlined. The fourth and last objective is the interpretation of the observed spectra. The question now raised is with regard to the mechanism emitting these spectra which men have learned to produce, to separate, and to record. What, in brief, is the structure of the atom or of the molecule which radiates spectral lines and bands? What is the key to these remarkable series that have been so precisely described by Rydberg, Moseley and others? Here it must be confessed at the very outset that no satisfactory solution has ever been obtained. Nevertheless in the year 1913, a young Danish physicist, Niels Bohr, succeeded in building upon the quantum theory of Planck, upon the electron theory of Sir J. J. Thomson and H. A.

Lorentz, and upon the experiments of Sir Ernest Rutherford and his school, an atomic structure which, in the ease and competence with which it explains the principal phenomena of spectroscopy, astonished the world. With a brief account of the development of Bohr's theory of atomic structure we must bring our sketch of the history of physics to a close.

It is evident at the outset that any satisfactory picture of the atom must explain how each element comes to have an atomic weight which is characteristic of that particular element. It must also explain how each element comes to have a characteristic spectrum. It ought to explain why any two substances brought into contact become electrified, one of them positively, the other negatively. It ought to tell us why the electrons taken from any one element are identical in properties with those from any other element. Radioactivity ought certainly to follow as a consequence from a true atomic structure.

The great paper[44] in which Sir J. J. Thomson described the experimental and quantitative properties of cathode rays in 1897 may be considered as giving the first clue to this structure. Here it was demonstrated that however the atom may be built up, the electron—which Thomson then called the corpuscle—must be one constituent.

The second contribution to this modern atom was given us by Professor Max Planck of Berlin long before its importance as a foundation stone of atomic structure was recognized. The theory that energy is radiated in discrete, finite bundles, or quanta, was enunciated by Planck

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[44] *Philosophical Magazine*, 44, pp. 293–316.

Max K. E. L. Planck (Born 1858)
German mathematical physicist; inventor and expositor of the quantum theory of radiation

in 1901.[45] Here Planck does not assert that energy itself is discontinuous or discrete; he merely insists that the energy must attain a finite and definite value, $h\nu$, before the resonator or oscillator can send out radiation or absorb radiation. In this paper, he evaluates the universal constant h as 6.55×10^{-27} erg seconds and defines ν as the frequency of the radiation emitted. The quantum, as Planck defines it, is therefore a perfectly definite quantity. His reasons for adopting the quantum view would here lead us too far afield; but the reader who cares to follow them will find the whole story admirably set forth by N. M. Bligh.[46] The effective manner in which Planck's theory is utilized by Bohr a dozen years after its announcement will appear shortly.

The third clue to atomic structure was given by Sir Ernest Rutherford[47] some ten years later, when he and his collaborators rendered it highly probable that practically the whole mass of the atom is concentrated in a minute central nucleus, about which electrons circulate in planetary orbits.

At the time when Rutherford's paper appeared (1911) there was, however, one outstanding difficulty with his, and all similar, atomic models, such as the earlier one of Sir J. J. Thomson, namely, that an electron revolving about a central nucleus is an accelerated body—accelerated toward the center—and hence must, according to the well-established electromagnetic theory, be a radiating body; and if a radiating body, its energy must be constantly diminishing; and therefore, the electron itself must finally fall into the central nucleus. The experimental fact is, of course, that a gas under ordinary conditions is *not* giving off atomic radiation in this manner. It was in the year 1913 that Dr. Niels Bohr of Copenhagen came upon the stage and showed how this difficulty might be avoided.

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[45] *Drude's Annalen*, 4, p. 553, 1901.

[46] *Evolution and Development of the Quantum Theory*, Longmans, Green and Company, 1926.

[47] *Philosophical Magazine*, 21, p. 669, 1911.

Bohr's approach to the structure of the hydrogen atom, the only atom yet thoroughly understood, was made through the following steps. He assumed Rutherford's atomic model and applied to it the following five assumptions which are cited from the last of his three highly original papers:

"1. That energy radiation is not emitted (or absorbed) in the continuous way assumed in the ordinary electrodynamics, but only during the passing of the systems between different 'stationary' states.

"2. That the dynamical equilibrium of the systems in the stationary states is governed by the ordinary laws of mechanics, while these laws do not hold for the passing of the systems between the different stationary states.

"3. That the radiation emitted during the transition of a system between two stationary states is homogeneous, and that the relation between the frequency ν and the total amount of energy emitted E is given by $E = h\,\nu$, where h is Planck's constant.

"4. That the different stationary states of a simple system consisting of an electron rotating round a positive nucleus are determined by the condition that the ratio between the total energy, emitted during the formation of the configuration, and the frequency of revolution of the electron is an entire multiple of $h/2$. Assuming that the orbit of the electron is circular, this assumption is equivalent with the assumption that the angular momentum of the electron round the nucleus is equal to an entire multiple of $h/2\pi$.

> "5. That the 'permanent' state of any atomic system—i.e., the state in which the energy emitted is maximum—is determined by the condition that the angular momentum of every electron round the centre of its orbit is equal to $h/2\pi$."[48]

The reader will observe that the ordinary laws of electromagnetism are here thrown overboard and the electron is allowed to revolve in its orbit without radiating; while on the other hand, the laws of ordinary dynamics hold so long as the electron remains in its orbit. What happens during the interval in which the electron jumps from one permissible orbit to another Bohr does not explain; but satisfies himself (for the present at least) by saying that during this interval the atom radiates homogeneous light waves, that is light belonging to some one line in the spectrum of the element to which that atom belongs. It is pointed out that, according to this theory, the intensity of any line in the spectrum depends upon the number of atoms which are undergoing the particular transformation which gives rise to that line.

Contrary to a widespread and popular impression, men of science do not throw the achievements of the past into the discard; instead of this, they modify and build upon these achievements. Einstein's achievement in relativity had the effect of slightly modifying Newton's law of gravitation; but that law did not go to the scrapheap. So here Bohr makes it probable that the ordinary laws of electrodynamics do not hold for systems of atomic dimensions; but the rules of nature formulated by Oersted, Faraday, Neumann, Maxwell and Hertz for electrical systems of ordinary dimensions remain intact. Once this fact was recognized, Bohr's view received wide and enthusiastic acceptance. The acclaim which his theory obtained can, however, only be understood in the light of its success in not only explaining radiation in general, but even in predicting the positions (wavelengths) of the lines in the various series. To appreciate just what Bohr accomplished in 1913, it is therefore necessary to follow through the few simple algebraic equations of motion from which he derives the frequencies of spectral lines and obtains the same numerical values which Rydberg had formulated from the wavelengths obtained in the laboratory by previous observers. There is nothing in the algebra more difficult than is offered by almost any one of the problems which a lad solves during his first year in the high school.

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[48] *Philosophical Magazine*, **26**, p. 874, 1913.

THE ATOMIC SPECTRUM OF HYDROGEN

No further apology is needed for the introduction here of Bohr's argument for the structure of the hydrogen atom. Since no hydrogen atom has ever been observed to lose more than one electron, Rutherford assumed it to consist of a nucleus about which a single electron revolves. If m be used to denote the mass of this electron, revolving in a circle of radius r about the central nucleus having a positive charge $+E$, then the attraction between the electron (which has an equal negative charge, $-e$) and the nucleus will be $\frac{Ee}{r^2}$, and this attraction will furnish the

SIR ERNEST RUTHERFORD (BORN 1871)

Director of the Cavendish Laboratory, largely responsible for present views concerning the disintegration of matter and concerning atomic structure

centripetal force necessary to keep the electron moving in its circular orbit with speed v, provided

$$\frac{m\,v^2}{r} = \frac{E\,e}{r^2} \qquad \text{..................Eq. (i)}$$

From this *equation of motion*, as it is called, one may easily obtain the period of the orbital motion as follows. Let ω be angular speed of the radius vector of the electron, r in figure 13, and T the period of the motion; then the angular momentum of the electron is $mr^2\,\omega$ which may also be written mrv and obtained at once from equation (i), thus

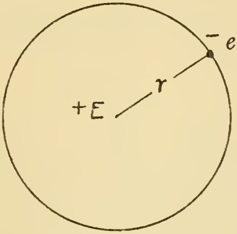

FIG. 13. AN ELECTRONIC ORBIT IN A HYDROGEN ATOM

$$mrv = m\,r^2\,\omega = \sqrt{E\,e\,m\,r} \qquad \text{..........Eq. (ii)}$$

Hence for T, which by definition is equal to $2\pi/\omega$, one has

$$T = 2\pi\sqrt{\frac{m\,r^3}{E\,e}} \qquad \text{..............Eq. (iii)}$$

The kinetic energy of the electron is, of course, $1/2\ mv^2$, and from equation (i) it follows immediately that $1/2\ mv^2 = 1/2\ \frac{Ee}{r}$.

For the potential energy, Bohr assumes as a zero-level, an orbit which is infinitely distant from the nucleus. The potential energy of unit electric charge at distance r from the center being $-\frac{E}{r}$, it follows that the potential energy of the electron is $-\frac{Ee}{r}$; and hence one has for the total energy, W,

$$W = \frac{1}{2}\frac{E\,e}{r} - \frac{E\,e}{r} = -\ 1/2\ \frac{E\,e}{r} \ldots\ldots\text{Eq. (iv)}$$

Up to this point any radius is possible for the orbit of the elecron; but Bohr now employs his fourth assumption to determine the only permissible orbits for the electron, namely, those for which the angular momentum of the electron is an exact multiple of $h/2\pi$ where h is Planck's constant.

In other words,

$$m\,v\,r = m\,r^2\,\omega = n\,\frac{h}{2\,\pi} \ldots\ldots\ldots\ldots\text{Eq. (v)}$$

From this equation,

$$r^4 = \frac{n^2\,h^2}{4\,\pi^2\,m^2\,\omega^2}$$

From equation (ii)

$$r^3 = \frac{E\,e}{m\,\omega^2}$$

Hence by division

$$r_n = \frac{n^2\,h^2}{4\,\pi^2\,m\,E\,e} \text{...............Eq. (vi)}$$

whence it appears that the radius of the orbit increases as n^2. The oribital speed v of the electron now follows at once from equations (ii) and (vi)

$$v = \sqrt{\frac{E\,e}{m\,r}} = 2\,\pi\,\frac{E\,e}{n\,h} \text{...........Eq. (vii)}$$

whence one passes immediately to the total energy, W, which has already been found numerically equal to $1/2\ mv^2$.

$$W = \frac{2\,\pi^2\,E^2\,e^2\,m}{n^2\,h^2} \text{.............Eq. (viii)}$$

Bohr here applies his third assumption that the energy radiated by the atom in changing from a stationary state characterized by n_2 to another characterized by n_1 is given by $h\nu$ where again h is Planck's constant and ν the frequency of the radiation. In other words

$$W_2 - W_1 = h\,v$$

or

$$\nu = \frac{W_2 - W_1}{h} = \frac{2\,\pi^2\,E^2\,e^2\,m}{h^3}\left(\frac{1}{{n_2}^2} - \frac{1}{{n_1}^2}\right) \text{..Eq. (ix)}$$

If c denotes the speed of light, one has for the wave number, $\frac{\nu}{c}$, the following expression:

$$\text{Wave number} = \frac{2\,\pi^2\,E^2\,e^2\,m}{c\,h^3}\left(\frac{1}{n_2{}^2} - \frac{1}{n_1{}^2}\right) = N\left(\frac{1}{n_2{}^2} - \frac{1}{n_1{}^2}\right)$$

which is Rydberg's equation when

$$N = \frac{2\,\pi^2\,E^2\,e^2\,m}{c\,h^3} \ldots\ldots\ldots\ldots\ldots \text{Eq. (x)}$$

It had been well known for many years that the universal constant N was very approximately 109675; and therefore the supreme test of Bohr's theory of the hydrogen atom came when he substituted the accepted values of the constants which appear in the right hand member of equation (x). These values are as follows:

$e = 4.77 \times 10^{-10}$ E.S. units

$E = -e$, in the case of hydrogen

$m = 0.901 \times 10^{-27}$ grams

$h = 6.554 \times 10^{-27}$ erg-seconds

$c = 2.9986 \times 10^{10}$ cm/seconds

From equation (x), therefore, $N = 109061$.

Such a striking verification of Bohr's view produced great confidence in nearly every mind that seriously followed it. The upshot of the matter was that a plan something like that represented in figure 14 was adopted for the structure of the hydrogen atom. Here the first six orbits of the electron are shown; and the electron-falls which produce the first three lines of the Lyman, Balmer and Paschen series are here indicated by straight lines.

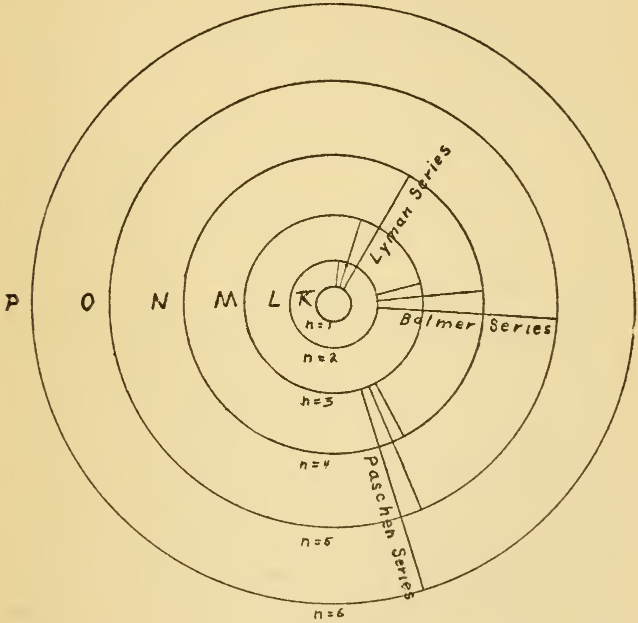

FIG. 14. BOHR'S EXPLANATION OF THE HYDROGEN SERIES

The first spectral line of each series is emitted when the electron falls from an orbit where $n_2 - n_1 = 1$; the second line from an orbit where $n_2 - n_1 = 2$; and so on, n_1 being a constant for the entire series. Here, of course, n_1 and n_2 have the same meaning as in equation (ix). If we put

$n_1 = 1$ in Bohr's formula we obtain the Lyman ultraviolet series; but if $n_1=2$, we get the Balmer series. Finally putting $n_1=3$, the Paschen infra-red-series is obtained.

At each jump of an electron to a smaller orbit there is a diminution of energy in accordance with equation (viii). When absorption of energy occurs the electron is displaced to a larger orbit with a corresponding increase of energy in the system.

Sommerfeld of Munich has demonstrated other brilliant verifications of Bohr's idea. Bohr, Wright and Hulburt have explained, on these same general principles, the continuous spectrum of hydrogen which overspreads the linear spectrum and extends beyond the limit of the Balmer series into the ultraviolet.

Many other investigators have extended these and similar principles to the examination and formulation of the spectra of the other more complicated elements of the Periodic Table. The main results are admirably summarized by Professor A. Fowler in his *Report on Series in Line Spectra* (London, 1922). The manner in which men such as Fowler and Nicholson in England, Saunders, Meggers, and Russell in America, Paschen and others in Germany have derived order from a collection of wavelengths which one generation ago was utter chaos is nothing short of amazing.

These modern extensions hardly fall within the scope of this book; but it ought perhaps to be added that the highly formal and artificial nature of many of these schemes are fully recognized by the men who have produced them. The mechanism of radiation which occurs during the leap of the electron from one orbit to another remains a mystery. However, even if some more satisfactory physical explanation is later arrived at—as it doubtless will be—the present generation can never forget the tremendous inspiration which came from these pioneers who had the courage to abandon the classical mechanics the moment they reached the atomic field and found the principles of Newton no longer a reliable guide.

The new dynamics, which shall prove itself as well adapted to handle the microstructure of the atom as that of the *Principia* was to describe the macrostructure of the solar system, is just appearing on the horizon. The Newton of the micromechanics is perhaps already with us and not yet fully recognized.

The reader who would complete this hasty sketch of the history of physics must not only fill the many lacunae—great branches of physics which have not even been mentioned—but he must also acquaint himself with the significant rôle which has been played, especially since medieval times, by the various academies of science, those groups of scholars which have come together in a sociable way and have contributed much toward clear thinking, human sympathy, and productive inspiration. The history of these institutions from the Lyceum of Aristotle at Athens and the Museum at Alexandria down through the Lyncei and the Florentine Academy, the Academy of Sciences at Paris, the Royal Society of London, the Berlin Academy, the American Philosophical Society established by Franklin, and a host of others makes a story quite too long for recital here.

Nor would any sketch of this subject be complete without some account of those great international organizations which have from time to time come together in the interests of a large, generous and cosmopolitan scientific spirit, ignoring all bounds of language and nationality. To meetings of this type we owe much of our knowledge of the earth and the stars. To the International Bureau of Weights and Measures we owe a great part of our mutual understanding in physics. To the International Union for Solar Research, launched mainly through the initiative of Dr. George E. Hale, we are indebted for a common nomenclature, for the establishment of important values, and the exchange of helpful ideas. The British Association for the Advancement of Science and a series of International Electrical Congresses have given us not only standards and units in electrical science but also standards of clear thinking. One is tempted to believe that gatherings of this type are not without influence in securing the peace of the world. In Paris at least, during the International Congress of Physics held in 1900, the peace of the world was, as the late Professor A. G. Webster said in addressing that assembly, a *fait accompli.*

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